AN ENVIRONMENTAL ASSESSMENT OF RECYCLING OPTIONS FOR USED LUBRICATING OIL IN SOUTH AFRICA

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By

Bryne Rwodzi
B.Sc. (Chemical Engineering) UCT

Department of Chemical Engineering
University of Cape Town
Rondebosch, 7701
South Africa

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Summary

There is concern over the fate of used oils as their chemical and physical constitution renders them potentially hazardous to soil water and air quality.

In South Africa, over 300 million litres of virgin lubricating oils have been sold annually since 1998. In 1999 about 57 million litres of used oils were collected, with about 70 % of the collected oils being recovered by the ROSE Foundation, a non-profit inter-industry organisation formed by the main lubricants companies in South Africa for the purpose of managing used lubricating oils. Post-collection management of used oils has focused on distributing the collected oil to selected recycling operations whose utilisation or processing is monitored and audited for satisfactory environmental performance by independent assessors contracted by the foundation. This current strategy for post-collection used oil management is one in which interrelated used oil concerns are managed independently, with no relationship between environmental management strategies and policies employed during the extraction and manufacturing stages of lube oils to the collection and re-use of used oil.

The approach currently being used for post-collection management of is thus one that effects site-specific improvements to recycling operations but cannot be used in making a quantifiable differentiation of the environmental performance of the different recipients of the used oil. Based on this current management method, at most site-specific, incremental environmental improvements can be realised, but there would be no means of comparing the performance of two different recycling options.

A study carried out with the aim of overcoming the limitations of current strategies for used oil management in the country is presented in this thesis. The goal of the study, was to develop a Life Cycle Assessment (LCA) based tool for comparing and evaluating the environmental performance of selected used oil management scenarios in South Africa. The LCA based tool presented a broad based strategy for used oil management which not only compares two different options but which can predict the performance of a recycling option within the context of the entire lube oil manufacturing, use and re-use system. The assessment tool was used to draw first conclusions on the performance of different options for used oil management.

The LCA, which was comparative in nature, was carried out on the activity of managing used lubricating oil and the functional unit proposed for representing this activity is 1000 kg of collected used oil. The activity of managing used oil was considered as being carried out in a life cycle system consisting of the main sub-stages; crude oil extraction, base oil refining, blending of lube oils, lubricating oil use, used oil post-use collection and finally recycling through one of a selected number of used oil management scenarios. The following are the used oil management scenarios selected for the study:

- Burning of untreated used oil for energy recovery in an industrial furnace
- Burning of untreated used oil for energy recovery in a cement kiln
- Burning of reprocessed used oil in an industrial furnace
- Burning of reprocessed used oil in a tunnel kiln brick-making furnace
- Re-refining of used oil employing a process which consists of a preflash stage, vacuum distillation, propane deasphalting of vacuum bottoms and product finishing through hydrotreating.

In the first four options, it was assumed that used lube oils would replace HFO as a fuel. Further, because the LCA was comparative in nature, the performance of the selected scenarios would be independent of the common life cycle stages, i.e. blending, use and collection, and these were thus left out in the analysis.

In setting the functional system boundaries the following elements were placed outside the boundaries:

- Lubricating oil losses during use (i.e. the study focuses on the fate of collected used oil)
- Lubricating oil additive manufacture and blended lube oil product distribution
- The production and distribution of refinery products other than lubricating oil

An LCA based model was constructed using TEAM™ 3 software by Ecobilan. This was used to investigate and evaluate the performance of the selected scenarios. Life cycle inventory data used in building the model was collected at the South African base oil refineries from logged day-to-day averaged production data for the relevant units in the refineries. Published articles, surveys and emissions tests data were used in building the data modules for the energetic use and re-refining options. Relevant data modules provided in the LCA software were also used and where data was unavailable assumptions were made.

The results generated from the model were used to compare the performance of the selected scenarios based on a selected number of inventory flows considered to be important environmental performance indicators in South Africa as well as using Life Cycle Impact Assessment (LCIA) categories.

The inventory results showed that the benefits of re-refining are derived from reduced emissions of base oil refining as well as from the reduction in the flow quantity for inventory results whose values are influenced mainly by their content as contaminants in used oil. Of the nine selected inventory flows re-refining presented superior inventory results for fuel energy use, lead emissions, nitrogen oxides emissions and for oils released in effluent.

In the energetic use scenarios used oil was assumed to substituted heavy fuel oil (HFO) burning in respective applications. The results showed that the benefits of the energetic use scenarios are derived from avoiding the impacts that would be associated with the production and combustion of an equivalent energy quantity of HFO. Of the selected inventory flows the energetic use scenarios presented superior performance for coal consumption, water use, the emission of sulphur oxides and particulates as well as for the quantities of chemically polluted water produced. The inventory results also showed differences in performance among the energetic use scenarios. Such differences arise from the different degree to which pollutants are fixed into solids during the burning, and from the extent of reprocessing prior to use as a fuel.

The Life Cycle Impact Assessment (LCIA) results also showed that the scenarios presented varying environmental performance for the assessment categories. Re-refining offers the best performance on potential contributions to aquatic ecotoxicity, eutrophication and photochemical oxidant formation potentials. The energetic use scenarios give the best performance for two of the remaining 3 LCIA categories with some uncertainty remaining on contributions to global warming potentials, resulting from uncertainties in inventory data quality. The burning of untreated oil in industrial furnaces would result in the lowest releases of substances causing air acidification and the scenario in which reprocessed oil is burned in industrial furnaces releases the lowest amount of substances attributed to negative human health effects.

Based on the assessment of the selected inventory results and the Life Cycle Impact Assessment, it would be difficult to present one management scenario which could be said to offer the best overall environmental performance based on the results of the LCIA. It is therefore recommended that other factors be considered in assessing the overall performance of a management scenario. Factors that could be considered include weighting the relative importance of the selected impact categories as well as considering the logistical and economic viability of the scenario.

It is proposed that the model developed be augmented by more detailed and accurate data in a number of categories, to be used to continuously improve post-collection management of used oils in South Africa.

Dedication

kuna Makaita Jasmine.

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Glossary of Acronyms

ASTM	American Society of Testing and Materials
API	American Petroleum Institute
APR	Association of Petroleum Re-refiners
BS&W	Bottom Sediments (Solids) and Water
CCME	Canadian Council of Ministers of the Environment
CONCAWE	European Oil Companies' Organisation for Environment, Health and Safety
DEAM™	Data for Environmental Analysis and Management
EC	European Community
EDIP	Environmental Design of Industrial Products
EPA	Environmental Protection Agency
EU	European Union
GWP	Global Warming Potential
IPA	Impact Pathway Analysis
IPCC	Intergovernmental Panel for Climate Change
ISO	International Standards Organisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODP	Ozone Depletion Potential
PAH	Polyaromatic Hydrocarbon
PCB	Polychlorinated Biphenyl
PCOP	Photochemical Ozone Creation Potential
PDA	Propane Deasphalting
PNA	Polynuclear Aromatic
SABS	South African Bureau of Standards
SAE	Society for Automotive Engineers
SETAC	Society of Environmental Toxicology and Chemistry
TDA	Thermal Deasphalting
TEAM™	Tools for Environmental Analysis and Management
VOC	Volatile Organic Compound
WRLI	World Reserves Life Index

Chapter 1

Introduction

1.1 USED LUBRICATING OIL: AN ENVIRONMENTAL CONCERN

Used lubricating oil can be defined as oil from industrial and non-industrial sources that has become unsuitable for its original purpose due to the presence of impurities or the loss of original properties. Generally the term embraces spent automobile lube oils and spent industrial oils including those used for lubrication, refrigeration and process applications. Used oil is often considered a hazardous waste normally containing potentially harmful constituents accumulated during use. Improper used oil disposal impacts negatively on the environment by contributing to air pollution, soil and water pollution, as well as having potential for direct human health impacts. (Cabrita et al, 1996; Hakes et al, 1997; Beiring, 1993)

The fate of used oils is a matter of intense environmental concern and in many countries legislation exists to monitor, regulate and control the disposal of used lubricating oil. (Used Oil Working Group, 1997) In addition to promulgating various items of legislation on used oil disposal most developed countries have commissioned extensive studies to develop environmentally sound strategies for used oil disposal, and to search for better alternatives to the present patterns and practices of used oil disposal. (Used Oil Hearing, 1977; Waste Oil Recovery Hearing, 1982, CCME Report, 1989; CONCAWE Report, 1996; Used Oil Working Group, 1997; Used Oil Management Conference, 1999)

Studies on used oil management have focused on assessing and comparing the three main options that are available for used oil disposal, namely; burning for energy recovery, reprocessing to remove basic contaminants from the oil to a standard required for the intended application, and re-refining the used oil to restore it to a functional state and purity that is equivalent to that of virgin lubricating base oil. Most of the published work on used oil management reviews the following factors that will determine the effective environmental performance of a used oil management strategy:

- Used oil collection programs and handling during collection (Arner, 1989; Used Oil Working Group, 1997; Norton, 1999; Gilbert, 1999)

- The environmental and technical performance of a variety industrial applications in which treated or untreated used oil may be used as a fuel. These industrial applications include commercial and industrial boilers, cement kilns and space heaters. (Berry et al, 1975; Used Oil Re-refining Hearing, 1977; McKendry-Smith, 1989; CCME Report, 1989; McCabe and Newton, 1997)

- The environmental and technical performance of various used oil reprocessing and re-refining technologies that have been developed or are currently under development. (Oliverson, 1975; Walters, 1975; Allen, 1976; Muller, 1894; Pyziak and Brinkman, 1993; CONCAWE Report, 1996)

- The technical, economic and legislative scenarios that have been investigated and implemented for managing used lubricating oils. (Ball et al, 1977, Bowen 1980; Pedal, 1980; Beiring, 1993; Used Oil Working Group, 1997; Ashauer, 1999; Williams, 1999; Heath, 1999)

Efforts to determine what may be considered the most environmentally sound management and technology option for disposing used lubricating oil are ongoing, motivated by marketers of used oil treatment technologies, as well as environmental managers seeking to develop management strategies specific to their socio- and geo-political settings. Most comparative studies that have been carried out have been site or equipment specific, seeking to investigate the environmental and/or economic gain that may be derived by replacing either a lubricant or fuel with a product derived from used lubricating oil in a given application. Examples of this type of comparative study include:

- Assessing the environmental performance of replacing fuel oils in selected industrial applications with used lubricating oil products, (McKendry-Smith, 1989; Berry et al, 1989; Cabrita, 1996; Mozes, 1997)
- Assessing the techno-economic and environmental performance of replacing virgin lubricating oils with re-refined oil, (Hsu, 1980; Kalnes et al, 1989; Brinkman and Dickson, 1995; McKeagan, 1992; Giovanna et al, 1999; Davies, 1996)
- Assessing the technical and environmental performance of blends such as, used lubricating oil-asphalt and used lubricating oil-residual oil fuel products. (Coghill, 1998)

However, a number of comparative investigations have been carried that have sought to use environmental assessment tools that enable a broad based, integrated approach to assessing used oil management options as systems that include a number of sub-stages that are defined as constituting a management scenario. These broad based comparative studies have focused on comparing burning options to re-refining options in used oil management, and are carried out with the aim of informing national or regional strategic policy on used oil waste management.

Thompson and Brinkman (1980) presented a mass and energy balance based comparison of burning and re-refining. The researchers quantified the potential material and energy commitments as well as savings that could be derived in a used oil management system incorporating crude oil extraction, refining and a recycling option.

At least four environmental Life Cycle Assessment based comparative analyses of re-refining and burning as used oil management options have been carried out and published in the European Union. (Davies, 2000) For example, Vold et al (1995) were commissioned by the Norwegian ministry of the environment to carry out a screening life cycle assessment to compare the environmental and resource consumption impacts of two systems; one for the burning of used lubricating oils and the other for the re-refining of used lubricating oils.

Thompson and Brinkman (1980), and Vold et al (1995) concluded from their work that re-refining was the better management option for used lubricating oil while other broad based investigations have produced inconclusive results (Davies, 2000).

1.2 USED LUBRICATING OIL MANAGEMENT IN SOUTH AFRICA

Used oil management can be divided into three broad categories which are; collection, recycling and disposal.

Used oil collection involves the set up and management of systems that enable the recovery of used lubricating oils. Used lubricating oil collection programs are set up primarily to prevent illegal dumping, to keep used oil separate from other classes of contaminants so as to improve the economics of recycling and to ensure that collected oil is recovered safely and managed in an environmentally acceptable way. (Arner, 1989)

Used oil recycling embraces activities that put recovered oils to a controlled end-use, which utilises the used oil's potential value. Used oil recycling and downcycling options can be broadly categorised into three groups:

- Controlled disposal in applications such as wood pole oiling, road oiling for dust control and use as a metal working oil.
- Burning treated or untreated used oil to recover its energy value.
- Treating the used oil and re-employing in designated lubricant functions.

Used oil disposal involves the use of facilities that do not utilise the oil's potential value (lubrication and/or heating). Disposal methods include burning in waste incinerators, dumping in sanitary landfills, dumping into municipal sewers and indiscriminate dumping. (CCME, 1989)

Some of the recycling methods and almost all of the disposal methods have been classified as environmentally unacceptable methods of used oil management, while uncontrolled disposal methods indicate the absence of a used oil management strategy. (CCME, 1989; Pyziak and Brinkman, 1993) Used oil management in South Africa can also be presented under the three broad categories as collection, recycling and disposal. The activities conducted within these broad management categories will be presented below.

1.2.1 Used Oil Collection

Over 300 million litres of virgin lubricating oil were sold annually, in South Africa since 1998. Approximately 57 million litres of used lubricating oil were collected in 1999, representing some 16 % of the total sold lubricants, while the remainder of the collectable used oil was disposed of indiscriminately and cannot be accounted for. (Norton, 1999)

During the era of sanctions the Nationalist Government recognised used oils as a strategic reserve and made it law that all used lubricating oils be collected and recycled. A legislated levy was put on all virgin lubricating oils sold in South Africa as a cost to cover used oil collection. However no use was made of the levy to encourage environmental improvements for the processes and operations utilising used lubricating oils. When sanctions on South Africa ended the legislated levy for used lubricating oil management was dropped. (Norton, 1999)

Since May 1995 the environmentally acceptable collection, storage and recycling of used lubricating oil in South Africa is managed principally by the ROSE Foundation. The ROSE Foundation stands for Recovery of Oil Saves the Environment, is a non-profit inter-industry organisation formed by the major oil processors and marketers in South Africa. All companies producing and marketing lubricating oil in South Africa are members of the Rose Foundation; the membership base is illustrated in Figure 1.1.

The main lubricant companies took it upon themselves without legislative coercion, to help protect the environment against the effects of irresponsible dumping and uncontrolled burning of used lubricating oils by forming and funding the ROSE Foundation.

According to its mission statement, the ROSE Foundation aims to increase the volumes of collected oil, ensure proper used oil handling during collection and use, and to add as much value as possible to the used oil within the strictest environmental standards.

The ROSE Foundation collects and manages about 70% of the volume of used lubricating oil collected in South Africa, through a contracted privately owned used oil collection company called Oilkol. Oilkol collects used oils from 15 000 sites around South Africa and delivers the oil to ROSE Foundation depots, which are also managed by Oilkol. Private collectors account for the remaining 30% of the collected used lubricating oil. (Norton, 1999)

Figure 1.1: Logos of the members of the ROSE Foundation

1.2.2 Used Oil Recycling

Used lubricating oils collected in South Africa are put to the following uses:

- Re-refining
- Reprocessing for subsequent burning in industrial furnaces
- Reprocessing for other uses
- Untreated burning in lime plants and in brick or tile kilns

About 11 % of the total volume of collected used oil is re-refined by the company Flexilube in Meyerton. This volume of oil is recycled into the market where it supplements the supply of virgin lubricating oils. About 76% of the total collected volume is reprocessed for subsequent burning. Examples of reprocessing operations are the Fuel Firing System (Pty) Ltd (FFS Refineries) reprocessing plants in Durban and Cape Town, and the Exoltech plant in Krugersdorp. The reprocessing plants currently operational in South Africa are largely constructed from salvaged refinery equipment although operators such as FFS Refineries have been involved in the design and operation of their own processing plants. (FFS Refineries Brochure, 1999) These treatment plants produce oils of varying qualities with most of them capable of producing quality low sulphur fuel, which may be blended with heavy fuel oils (HFO) before disposal. Reprocessed oils that are sold as fuel are burned in a wide variety of industrial applications which include commercial and industrial boilers, direct firing furnaces, ceramics kilns and in space heaters.

Reprocessed oils are also employed in other applications such as substituting metal working oils and a constituent in the manufacture of slurry explosives. Slurry explosives are manufactured by Bulk Mining Explosives at Carletonville in the Gauteng province. About 9 % of the collected and reprocessed volume of used lubricating oil is used in the manufacture of slurry explosives.

About 4 % of the total volume of collected used oil is burned as a fuel without prior treatment in lime kilns and brick kilns. Untreated used oil in these operations supplements or replaces the burning of heavy fuel oils, and is therefore dependent on the process equipment's handling of fuel with characteristics which are different to those for which it was originally designed and on the process' ability to completely destroy or contain the contaminants found in used oil.

The use of used oil for wood pole oiling and in road oiling for dust control has been documented by Norton (1999), however, the volumes of used oil consumed in these applications are not known. Used oil recycling activities such as road oiling for dust control and wood pole oiling, that release used oil directly into the environment without destroying it have been found to cause

adverse environmental effects (Pyziak and Brinkman, 1993) and they will not be considered as viable alternatives in used oil management in South Africa.

Figure 1.2 shows the location of recycling operations and used oil storage depots in South Africa.

1.2.3 Used Oil Disposal

Collection efforts in South Africa recover about 30 % of the total volume of collectable used oils. The larger proportion of the used oil volume cannot be accounted for, and its fate could be recycling or controlled disposal in small-scale industrial and farming applications; or indiscriminate dumping on land or in water.

Controlled and uncontrolled disposal methods release used oils into the environment without destroying it and are considered environmentally unacceptable methods of managing used lubricating oil. Role players in the collection of used oil in South Africa are continuously seeking ways to increase the volume of collected used oils so as to prevent its utilisation in controlled and uncontrolled disposal methods. (Norton, 1999)

1.2.4 Strategies for the Environmental Management of Used Lubricating Oil in South Africa

Norton (1999) claims that there exist client-marketer relationships between the collectors, recyclers and disposers of used lubricating oils. The independent collectors, who account for up to 30 % of the collected used lubricating oil and their recycling and/or disposing clients do not have a well-documented environmental management policy or structure. However, the ROSE Foundation which collects the bulk of the used lubricating oil, through a used oil collection company-Oilkol, seeks to add as much value to the collected used lubricating oil as possible within the strictest environmental standards. The ROSE Foundation has effected its policy of strict environmental controls in the used oil management process through the following means:

- The Rose Foundation contracted environmental experts to assess the environmental performance of the various used oil recycling and disposal operations that were potential recipients of used lubricating oils collected through the Rose Foundation. The Rose Foundation only entered into agreement to supply used lubricating oils exclusively to those industrial operations that were recommended as having the capacity to dispose of the oils without adverse environmental effects. (Norton, 1999)

- The Rose Foundation has set targets for environmental improvements and controls that are enforced at each recycling or disposal operation. The environmental targets have been designed by independent environmental practitioners and are implemented through a series of audits and controls focusing on the used oil recipients' chemical processes, house keeping and site management. Recipients of used oil collected by the Rose Foundation have to agree to regular environmental audits, and those operations that do not meet the assessment criteria will no longer be supplied used oil by the Rose Foundation. (Norton, 1999)

1.3 PROBLEM STATEMENT

The current strategy for used lubricating oil management in South Africa is one which has compartmentalised inter-related used oil environmental management problems into a number of independently managed stages. There is little, if any relationship in the strategies and practises employed in the environmental management of extraction and manufacturing stages of lube oils to the collection and re-use of the used oil. The relationship between the collectors of used oil, as represented by the ROSE Foundation, and the recyclers or disposers is one in which there is coerced environmental accountability.

The approach used by the Rose Foundation of performing environmental assessments on potential used oil recipients and on going environmental audits can be classified as end-of-pipe treatment strategies that do not provide a formal means of making a quantifiable differentiation of the environmental performance of different recipients of the used oil, such as an industrial furnace or a brick kiln. At most incremental environmental improvements that are made based on recommendations from auditors of individual sites can be realised, but there would be no means of comparing any two different recycling or disposal options.

Based on recognition of the limitations of the current strategies for used oil management in South Africa, the following problem statement will be presented:

There lacks a broad based environmental management strategy for used oil management in South Africa which not only can compare two different management options, but which can predict the environmental performance of a used oil recycling option, quantifying the benefits of the options within the context of the entire lube oil manufacturing, use and re-use system.

As the volume of collected used oil continues to increase, the current management strategies cannot provide a basis for formulating policies or strategies for distributing incremental volumes of used oil to new recipients. An environmental assessment method that can predict, in a quantifiable manner the potential environmental impacts of the various disposal routes is required as site specific environmental audits serve only to provide improvements to each disposal option. The environmental assessment method should enable each disposal option to be assessed based not only on the potential gains that may be derived from site specific improvements but must be able to review the disposal option's holistic environmental influences on upstream and down stream inter-related processes, as well as consideration of the quantifiable environmental improvements the oil product offers as a replacement for alternative products in the same application.

1.3.1 Life Cycle Assessment - A Tool to Evaluate the Environmental Performance of Used Oil Management Options in South Africa

Eight studies are reported to have been carried out in the European Union and the USA that have sought to use environmental assessment tools that are capable of making comparative analyses of different used oil management options. (Thompson and Brinkman, 1980; Davies, 2000) The majority of these studies, which have been carried out in Europe have used comparative Life Cycle Assessment as an environmental assessment tool. The results of the LCA studies have been used in strategic decision making as well as informing on environmental and legislative policies for used lubricating oil management for the European Union (Davies, 2000)

Prior to this research no LCA work had been done in South Africa on comparing different used oil management options. The results of comparative LCA studies on used oil management options conducted in the European Union cannot be considered to be directly transferable to the South African environment for the following reasons:

- Used oil management scenarios, i.e. policies and practices for used oil collection, recycling and disposal are different in South Africa when compared to the European Union. (CONCAWE Report, 1996; Used Oil Working Group, 1997; Norton, 1999)

- The operating parameter, process energy efficiencies, inputs and products specifications as well as waste and environmental emission restrictions for processes constituting the used lubricating oil management life cycle are different for South Africa when compared to the European Union. (CONCAWE Report, 1996, Used Oil Working Group, 1997; Ecobilan Data Modules, 1999; Creswell, 1999; Norton, 1999; Davies, 2000)

- The Terms of Reference and system boundaries specified for carrying out the LCAs in the European Union will be different to the specifications for the South African study. (Vold et al, 1995)

This approach of using life cycle assessment for the consideration and comparison of the management options to be considered for used lubricating oil management has been chosen because traditional methods of environmental management that are currently being used as a basis for environmental assessments and environmental audits, such as Risk Assessment and Environmental Impact Assessment (EIA) tend to break up interrelated problems into smaller problematic units that are managed independently. This leads to efficient end-pipe technologies but cannot be effectively used in integrated preventive approaches that are now recognised as necessary in the optimization of solutions to large-scale inter-industry environmental problems such as the used lubricating oil problem in South Africa.

1.4 OBJECTIVES OF THE RESEARCH

The research carried out and presented in this thesis aimed to compare the technical and environmental performance of different technologies and waste management scenarios for used lubricating oils in South Africa. The main objective of the study was to examine and compare the environmental performance of different management options by a comparative process-focussed life cycle assessment, in order to inform policies and analyse practices on used lubricating oil recycling and disposal. In addition to this, the study was intended for assisting in identifying and rectifying process steps particularly harmful to the environment in the South African context for each management option under consideration. The findings of the study are aimed at informing strategic decision-making in the fold of managing waste oils in South Africa.

It was also the aim of the research to review the management systems and technologies currently being employed for used oil management in South Africa, and to use LCA as a basis for determining the environmental improvement opportunities that may be presented by either improving currently operational systems or by introducing new technologies for used oil management.

The specific objectives presented for the research are:

- to review different management and technology options for used lubricating oil processing;
- to identify product, by-product and waste specifications for a number of critical management options and the associated technology;
- to carry out a comparative Life Cycle Assessment on selected options of managing used lubricating oils;

- to develop a technique whereby an LCA based model can be used to investigate and evaluate the environmental performance of specific scenarios for used lubricating oil processing in South Africa and thereby form a basis for recommending improvements;
- to recommend the best available management options and technologies in the South African context.

These research objectives were set with the recognition of the following factors in environmental management:

- There is a range of used oil management and processing technology options available for consideration in South Africa.
- Used oil management and process technology options, as applied in other countries and consequently other socio-economic, industrial and natural environments, are not necessarily optimally suited to South African conditions.

1.5 STATEMENT OF THE HYPOTHESES

Based on the given objectives of the research two main Hypotheses are proposed for investigation:

Hypothesis 1:

Comparative Life Cycle Assessment of the available used oil management and technology options will reveal significant differences in environmental performance and will serve to identify areas of improvement.

The following options currently being employed in used oil management will be discussed in the thesis with reference to the first hypothesis:

- Burning without prior treatment for energy recovery
- Reprocessing for subsequent energy recovery
- Re-refining

The results of studies carried out by other researchers using environmental assessment tools capable of making a comparative analysis on used oil management options have either produced inconclusive results or have recommended that re-refining was the better management option for used lubricating oils in their respective environments. (Brinkman and Thompson, 1980; Vold et al, 1995; Davies, 2000) Based on the conclusive results from some of the comparative studies in used lubricating oil management options, the second hypothesis for the thesis is presented overleaf:

Hypothesis 2:

Of the stated methods of used oil management, and working on the basis of applying the best available technologies for each management option, re-refining is the most environmentally sound solution for the management of used lubricating oils generated in South Africa.

1.6 APPROACH TO RESEARCH

In order to satisfy the objectives and prove the hypotheses of the research a comparative LCA was carried out to assess the existing and potential environmental impacts of employing the available recycling options for used lubricating oils in South Africa. After defining the goal and scope of the research, data was collected for the processes constituting selected used oil management life cycles and used to build an LCA software based model which formed the basis for investigating the environmental performance of selected scenarios for used lubricating oil management in South Africa. The results generated from the LCA software based model will be presented in the thesis and will form the basis for identifying the best used lubricating oil management scenario in South Africa as well recommending improvements to used oil management options.

1.6.1 Scope and Limits of Research

The Life Cycle study covered the entire life cycle of the used oil management options from crude oil extraction to ultimate used oil disposal. Since the LCA is comparative in nature processes and operations common to all alternatives were omitted in the study. The study also focused on mineral oil based used lubricating oils only, since synthetic oils provide, by quantitative comparison, minimal industrial application in South Africa and hence are expected to make minimal contribution to environmental degradation.

Lubricating oils are known to provide a wide range of industrial and automotive applications. However the waste oil stream that was considered in this study was based on a composite waste oil stream without consideration of the use-related source of the used lubricating oil.

1.6.2 Source of Information for the Research

Three broad categories of information were required to satisfy the objectives of the research and to prove the hypotheses presented in the thesis:

- Information on used lubricating oil management options and technologies currently employed in South Africa and elsewhere.
- Literature on LCA methodology and procedure, with particular focus on comparative LCA studies for waste management options
- Process data required for constructing life cycle inventories for the processes constituting the used lubricating oil management life cycles and technology options considered in the research.

Information of used oil management options and technology options, as well as on LCA methodology and procedure was obtained by carrying out extensive literature surveys, reviewing the results of comparative studies and through consulting experts on used oil management and LCA analysis.

It is well known and often emphasized that the quality of results presented from an LCA are critically dependent on the quality of data used in the inventory analyses. (ISO/FDIS 14041, 1998; Vigon et al, 1994; Graedel, 1998; Curran, 1993) Curran (1993) describes the following basic approaches that have been utilised for data gathering in LCA:

- Primary data collection, where the manufacturer directly describes how to produce the product and provides as much of the necessary data as possible.
- Secondary data, where published data such as articles, studies and surveys are used

- Assumptions, where the analyst makes assumptions about the parameters of the product's manufacture.

The bulk of the data used in the inventory analyses is primary data collected from process operations in the various sub-stages of the used lubricating oil life cycle. Where data was not readily available one or a combination of the following methods obtained it:

- experimental tests were performed around the process or process streams in question,
- data from LCA software databases on a similar process or process stream was used,
- literature values were used,
- estimates were made based on the best available information.

Life Cycle stages where secondary data was used in the research have been clearly indicated with aspects of data quality such as precision, representativeness, consistency and reproducibility being discussed.

1.7 THE STRUCTURE OF THE THESIS

Environmental Life Cycle Assessment is the tool that has been used in the assessment of the various options available for managing used lubricating oils. It is expected that a section of the target audience for this thesis will have inadequate knowledge on, or exposure to the comparative environmental Life Cycle Assessment technique used in the assessment of data, presentation and analysis of results for the research. For this reason the thesis is structured in a way to enable the reader to develop an understanding of the management of used lubricating oil while applying Life Cycle Assessment into reviewing the various solutions that may be applied.

The Chapters of the thesis are arranged as follows:

- The characteristics, management options and technologies employed in managing used lubricating oils are reviewed in Chapter 2. This is done to set the basis for performing the LCA and to identify possible technologies that may be considered in the assessment.

- In Chapter 3 Life Cycle Assessment as a tool for environmental management is reviewed. Its strengths and weaknesses are reviewed and the LCA methodology is explained.

- In Chapter 4 the goal and scope of the research are defined and a review of the methods available for presenting the research results is given.

- The processes and sub-processes selected for inventory building within the LCA system boundaries are individually reviewed in Chapter 5. In this chapter the description of selected processes, including material and energy balances, process flow data, as well as their concomitant environmental concerns are presented. The data collection process is reviewed and data issues are discussed. Any experimental work, assumptions and difficulties encountered in the inventory building process are also discussed.

- In Chapter 6 the LCA based computational model that used in the comparative assessment of the environmental performance of selected used oil management scenarios is described.

- In chapter 7 the results of the LCA analysis, generated from the computational model described in Chapter 6 are presented. The results and their interpretation will be based on a selected number of inventory flows, which may be considered to be important environmental performance indicators in South Africa. In this chapter sensitivity analyses are also carried out on the co-product allocation rules used in assigning environmental burdens to the inventory flows.

- In Chapter 8 the environmental performance of the selected used oil management scenarios is assessed based on a select number of Life Cycle Impact Assessment (LCIA) categories. The overall performance of the management scenarios will also be considered based on the LCIA categories.

- The assessment of the results with the aim of testing the hypotheses, determining the greatest contributing factors and assessing the scope for improvements is presented in Chapter 9. In this chapter conclusions on the effectiveness of LCA in reviewing the various options available for waste oil management as well as recommendations on the various management scenarios that have been considered in the LCA will be finally presented.

Chapter 2

A Review of Used Lubricating Oil Management Options

2.1 INTRODUCTION

This chapter presents a review of the options that are available for managing used lubricating oils. In the review used lubricating oil characteristics, management and technology options as well as their potential environmental impacts are discussed. Special reference is made to options that are employed in South Africa as well as those considered for future application.

In the review of the management of used lubricating oils is presented in three broad categories

- Controlled disposal,
- Burning to utilise energy value,
- Treating and re-employing in designated lubricating functions.

Indiscriminate disposal, a major environmental concern, will also briefly be referred to.

In each of these categories specific technologies that are used in managing used lubricating oils are discussed and their performance is evaluated based on their capacity for mitigating against the known environmental impacts associated with used lubricating oil disposal.

The specific objectives of the review are:

- To present information on the chemical and physical characteristics of used lubricating oils and to assess the types and levels of contaminants that are found in used lubricating oils.

- To review the health and environmental impacts that are associated with the handling, processing and disposal of used lubricating oil

- To review the management and technology options that are employed in treating used lubricating oils, and where information is available, review the reported strengths and weaknesses of the technology options.

- To review the extent to which the used oil management options that are presented in literature are used in South Africa.

The overall purpose of the review then is to present information on the used oil management and technology options that are to be considered in the Life Cycle Assessment presented later in the thesis.

2.2 CHARACTERISATION OF NEW AND USED LUBRICATING OIL

Lubricating oils may be classified as mineral oil (crude oil) based or synthetic oil based. Lubricants perform a large number of functions, some of which are specific to individual equipment being serviced and some common to all equipment. The functions include (Sequeira, 1989):

- reduction of friction and wear (lubrication per se.),
- dissipation of heat,
- control of rust and corrosion,
- prevention of excessive deposits,
- dispersion of use generated contaminants,
- establishment of sealing of critical parts.

Mineral oil based lubricating oils quantitatively provide the bulk of industrial service. Synthetic oils find use mainly in specialised functions. For this reason this thesis will focus on mineral oil based lubricating oils.

2.2.1 What is Lubricating Oil?

Virgin lubricating oils consist of lubricating base oils, which provide the basic lubricating function, and chemical additives, which provide or enhance the remaining functions of the lubricating oil.

Modern lubricating oils may contain up to 25% additives, depending on service involved. Some of the additives and their functions are listed in Table 2.1. Table 2.2 gives in more detail some of the chemical constituents of lubricating oil additives.

Table 2.1 Some types of additives and their functions

Main type	*Function and sub-types*
Acid neutralisers	Neutralise contaminating strong acids formed, for example, by combustion of high sulphur fuels.
Anti-oxidants	Reduce oxidation. Various types are: oxidation inhibitors, retarders; anti-catalyst metal deactivators, metal passivators
Corrosion inhibitors	The first type reduces corrosion of lead while the second type reduces corrosion of cuprous metals
Dispersants	Prevent deposition of sludge by finely dispersing any suspension of the insoluble material formed
Detergents	Reduce or prevent deposits formed at high temperatures, e.g. in internal combustion engines

Source: Neale, M. J., 1993

The base oils in lubricating oils are produced from crude petroleum by distillation. They consist of hydrocarbon based substances (paraffins, cyclo-paraffins, aromatics, etc.) of varying molecular weight and volatility, as well as minor but important amounts of other hydrocarbon derivatives.

There are many ways of classifying mineral oil based lubricating oils. They may be classified from the type of base oil used in their manufacture. This classification also accounts for the type of crude petroleum used and the point of extraction during the refining process. The major types of base oils used in the manufacture of lubricants are:

- Napthene pale oils
- Solvent neutral oils
- Bright stocks
- Cylinder oils

Lubricating oils may further be classified by their use. Table 2.3 gives some of the use-defined lubricating oils.

Lubricating oils are still further classified by the industries that use them, based typically on a chemical or physical property of the oil.
For example, the Society of Automotive Engineers' Specification No. 26 published in June 1911, laid foundations for what is still the definitive classification of automotive engine oils. The SAE viscosity numbers constitute a classification of crankcase lubricating oils in terms of viscosity only.

Other types of industrial classifications are:

- American Gear Manufacturers Association, AGMA Standard Specification for Lubrication of Industrial Enclosed Gearing
- National Lubricating Grease Institute, NLGI Consistency Classification for Greases
- Production Engineering Research Association, PERA Code for Lubricating Symbols (BP Industrial Lubrication, 1966)

2.2.2 What is Used Lubricating Oil?

Used lubricating oils can be defined as mineral or synthetic oils from industrial and non-industrial sources that have become unsuitable for their original purpose due to the presence of impurities or the loss of original properties. Generally the term embraces spent automobile lube oils and spent industrial oils including those used for lubrication, refrigeration and process applications.

There may be a variety of other definitions for used lubricating oil, however experience has shown that this material has to be defined precisely to avoid problems in the collection and treatment of used lubricating oils. The definition has to be sufficient for practical and juridical purposes. It is therefore necessary to know the composition and contaminants volumes that may constitute used lubricating oils.

2.2.2.a Contaminants in used lubricating oils

The composition of and the contaminants in used lubricating oils have a wide variety. This is a result of many factors, including the characteristics of the virgin oil and its use, as well as the collection/handling process associated with the used oil.

Used industrial oils are more diverse than used automotive oils because they perform a wider variety of functions. Therefore, the contaminants in used industrial oils will vary depending on function and level of use, as well as by the type of additive. Furthermore the components of the additive packages are diverse since most additive packages are custom-blended for particular needs. It is therefore impossible to identify a set of contaminants characteristic or expected to be present in used industrial oils.

The composition of collected used automotive oil, with proper handling, has in the past been described as remarkably uniform (Siemon et al, 1979). Variations in oil composition are usually due to extent of oil use, engine age, type and efficiency. Contaminants of particular environmental concern, typically found in waste automotive oils include lead, chromium, zinc, polynuclear aromatics, halogenated solvents and coolants.
(Pyziak and Brinkman, 1993)

The composition of waste oils may have changed to date and may be different from country to country. However all automotive oils meet SAE grades and may thus be expected to be homogeneous the world over. (Siemon et al, 1979)

Table 2.2 Lubricating oil additives and contaminants likely to deactivate them during use

Used oil type	Typical kinds of additives	Primary source and type of typical contaminants
Motor oils	**Antiwear**: zinc organo-dithiophosphates;organic phosphorous compounds	**Gasoline**:lead and lead compounds;gasoline;halogens
	Corrosion inhibitors: sulphonates; amine phosphates; organic phosphotides	**Additives**: zinc and zinc compounds; phosphorous compounds, etc.
	Detergents and Dispersants: calcium, magnesium, barium and zinc sulphonates, phosphonates, and phenates; alkenyl succinimides; acrylic polymers	**Combustion products**: polynuclear aromatrics; water; oxygenated compounds;sludge; varnish
	Viscosity index improvers: isobutylene polymers; acrylate polymers	**Fuel**: volatile liquid
	Antifoam agents: silicones; synthetic polymers	**Coolant leaks**: water,
	Pour-point depressants: polymethacrylates; polyacrylamides	Contamination: dirt; wear
	Antioxidants: zinc organo-dithiophosphates; hindered phenols; aromatic amines; sulpherised phenols	
Hydraulic and industrial oils	Many of the above plus:	Many of the above plus:
	Extreme pressure additives: organo-sulphur compounds; organo-chlorine compounds; lead compounds; amines	**Additives**: sulphur and sulphur compounds; chlorine and chlorinated compounds; fatty oils
	Emulsifiers: surfactants; suphonates; naphthenates; fatty acid soaps	**Contamination**: metal particles
	Antiseptics: alcohols; phenols; chlorine compounds	**Solvents**: volatile liquid

Source: [a]Used Oil Recycling Hearing, 1980

Table 2.3 Some use-defined lubricating oils

Engine oils	Paper machine oils	Refrigeration oils
Gear oils	Greases	Journal lubricants
Hydraulic oils	Metal working oils	White oils
Transmission fluids	Turbine oils	Industrial oils

[1]Source: Lubricant Base Oil and Wax Processing, Sequeira, A.,1994

Table 2.4 gives in detail, the average content of contaminants in samples of used automotive oils studied by the Danish Environmental Protection Agency. (Muller, 1984) As a more detailed analysis of automotive lubricating oil is given the relative variance in contaminants concentrations also increases.

Table 2.5 gives a comparison of used oil contaminants in different countries. The data is useful in establishing the trends of relative contaminant concentrations in the individual used oil samples. The comparison of the concentrations of contaminants in two different oil samples would not be useful as these values depend on other factors such as extent of oil use.

The data in Table 2.5 however seems to show similarity in some contaminant compositions such as water content, ash content and to a lesser extent lead (Pb) concentrations for the countries considered. Other contaminants such as barium (Ba), copper (Cu) and zinc (Zn) show a wide variation in concentrations for the countries considered. This is probably due to the fact that barium, copper and zinc are introduced into lubricating oils via the additive component (see Table 2.2). Since different lubricating oil producers use different additive components and concentrations, their concentrations will also vary in the used oils.

2.3 ENVIRONMENTAL CONCERNS REGARDING USED LUBRICATING OILS DISPOSAL

The fate of used oil is a matter of intense environmental concern as their chemical and physical constitution renders them potential hazards to soil, water and air quality. Each of these pollution categories will be discussed below.

2.3.1 Air pollution

The uncontrolled burning of untreated used lubricating oils may cause hazardous emissions of heavy metal particulates, principally lead (Pb). Pollutants emitted from the complete and incomplete combustion of the organic components in used lubricating oils are oxides of nitrogen (NO_x), N_2O, SO_2, P_2O_5, CO, CO_2 and some halogenated acids. Polyaromatic hydrocarbon compounds (PAHs) and Polychlorinated biphenyls (PCBs) can also be released from the burning of used lubricating oils.(Cabrita et al,1996)

2.3.2 Water Pollution

One liter of used oil can pollute up to a million liters of drinking water. (Hakes et al, 1997) Used oil dumped into drains fouls connector sewers and treatment plants, thus increasing maintenance costs and reducing treatment efficiency. (Resulting in more contaminated effluent) (Irwin, 1978) The discharge of excessive quantities of greases and oils causes problems for municipal sewage treatment plants. Greases and oils may overload the skimming devices, and block screens and other mechanical systems. Build-up of these materials in the biological sludges will cause difficulties in the subsequent treatment and disposal of these sludges. (Rimkus et al, 1975)

The disposal of used oil into bodies of water can severely disrupt surface water ecology through a number of mechanisms. First, since the hydrocarbons in water decompose microbially, this may

lead to eutrophication. Secondly, oily films on the surface, by blocking sunlight from aquatic plants and by reducing surface aeration, also prevent replenishment of waterborne oxygen by impairing both photosynthesis and direct entry of airborne oxygen. Third, oil contains noxious compounds which even in small concentrations can disrupt the feeding habits of water life. Finally, oil may contain toxic components which poison fish through their food chain. (Irwin, 1978)

Table 2.4 Averaged concentrations of contaminants for 14 samples of used automotive oil

Contaminant	Averaged concentration (µg/g)
Ash	0.76
Water and sediment	9.3
Elements	
Arsenic	16
Barium	68
Cadmium	1
Chlorine	2100
Chromium	6
Copper	41
Iron	210
Lead	1220
Magnesium	300
Nickel	3
Sulfur	4500
Vanadium	1
Zinc	940
Volatile organics	
Trichlorotrifluoroethanes	160
1,1,1,-trichloroethane	580
Trichloroethylene	490
Tetrachloroethylene	380
Toluene	2500
Dimethyl benzenes	1600
Semivolatile Organics	
Phenol	<10
Naphthalene	360
Phenanthrene/Anthracene	180
Pyrene	45
Benz(a)anthracene	18
Benzo(a)pyrene	<10
PCBs	<2

Source: Muller, 1984

Table 2.5 Composition of used motor oils for selected countries

species	[a]Australia(1978)	[b]Portugal (1996) Av. Of 28 amples	[c]Denmark (1984) Av. 14 samples	[d]Canada (1989)	[e]USA (1974)
Carbon (wt %)		82.6±0.5			86.3-86.26
Hydrogen (wt %)		13.5±0.3			13.69-13.61
Nitrogen (wt %)		0.38±0.03			0.03-0.54
Sulfur		0.95±0.06 wt %	4500 ppm	0.43 wt %	0.13-0.47 wt %
Water	*3-10 wt %	2.4±1.2 vol. %		11	**11
Sediment (wt %)	7 wt %	0.23±0.07 wt %			
Water and sediments(wt %)			9.3	11	**19
Ash (wt %)	1.2	1.09±0.07	0.76	1.01	
Volatiles (vol %)		5710 ppm	5		5-36
Pb (ppm)	*2000-3000	1500±119	1200	240	1-11000
Cr (ppm)		<10	6	177	
Ca(ppm)				1850	1052-1550
Cu (ppm)		20±1	41	1025	1-67
Cl (ppm)		569±50	2100	1600	0.03-0.11 wt %
Br (ppm)		319±44			
Mg (ppm)			300	559	1-200
P (ppm)				1250	650-1410
Zn (ppm)			940	480	560-1550
Ba (ppm)			68	48	2-1631
Fe (ppm)				1025	10-330
Halogens(ppm)		715±76	1610	1600	**3600
PCBs (ppm)			<2	5	**20.7
Specific gravity (15°C)		0.9			0.83-0.88
viscosity (40°C, mm^2/s)		90±5		99	61-80
Flash point (°C)		>18		60	**38
Heating value (MJ/kg)		43.7		38	**38.4

Sources[a]: Siemion et al, 1979
[b]: Cabrita et al, 1996
[c]: Muller, 1984
[d,2]: CCME Report, 1989 adopted from Franklin Associates Ltd., 1985; Rudolph, 1978; PEDCO-Environmental Inc., 1984
[e,1]: Linnard, Used Oil Re-refining Hearing, 1977
* : Salusinszky, 1981, **: Wentz and Basler, 1991

2.3.3 Soil Pollution

Disposal of used oil on soil may render land unproductive and contaminate surface and ground water.

Experiments carried out to investigate the effects of used motor oil on soil showed that high oil application resulted in microbial immobilization of nitrogen and other plant nutrients in the soil, resulting in drastically reduced crop yields. (Giddens, 1976)

2.3.4 Health Risks Associated with Used Oil

Valzquez-Duhalt (1982)(cited by Beiring, 1993) reviewed investigations on the mutagenicity, carcinogenicity and toxicity of used motor oil, and noted the following effects. Used motor oil has been shown to be mutagenic to bacteria, and in fact, more mutagenic than new oil. Certain non-carcinogenic hydrocarbons, as well as oil additives, can increase the detrimental effects of carcinogenic PAHs. Tumors have been induced by applying used motor oil to the skin of mice. Death and deformation have been reported from the external application of used motor oil to birds' eggs.

The detrimental effects of particular components of used oil have been studied at the level of individual organisms, particularly humans. The following quote gives an indication of such effects:

> The toxic constituents identified in used oil are presumed to have carcinogenic, mutagenic, teratogenic or other chronic or acutely toxic properties. In particular, tetrachloroethylene, trichloroethylene and 1,1,1-trichloroethane have the potential to cause liver and kidney damage in animals and humans above certain concentrations; toluene is known to cause central nervous system disfunction and is linked to reproductive disorders in humans. Chronic exposure to naphthalene may produce cataracts, hemolytic anemia and kidney disease in humans. Exposure to toxic metals – especially lead – above a certain level, is known to cause renal damage, cerabrovascular disease, heart failure, impaired liver and thyroid function, miscarriages and stillbirths in humans.
>
> (Beiring, 1993)

2.3.5 Legislation in different countries regarding used oil management

Most developed countries have national or federal legislation concerning used lubricating oil disposal. However, the extent of enforcement of legislation differs from country to country depending on the recognition of the hazards related to used lubricating oil disposal.

Appendix A lists the legislation enforced in selected countries. The table is not exhaustive in its approach but rather serves to provide insight into different policies on used oil management.

2.4 MANAGING USED LUBRICATING OILS

Subsequent to the collection of used lubricating oils they have to be put to a controlled end-use. There are many post-collection management options available for used lubricating oils, which can be broadly categorised into three groups:

- Controlled disposal
- Burning to utilise energy value
- Treating for re-use and recycling

Within each of the proposed management categories there are many classes or methods of used oil management options. These will be discussed under the three broad categories in for managing used oils. For completeness, indiscriminate disposal will be discussed alongside controlled disposal, while reprocessing which can be an intermediate step in both the second and

third category will be discussed in its own section. The discussion of re-use and recycling will be split into two sections.

2.4.1 Used Lubricating Oil Disposal

Used Lubricating oil disposal involves the use of facilities that do not utilise the oil's potential value (lubrication and/or heating). The Canadian Council of Ministers of the Environment Report (CCME) (1989) on used oil management in Canada places used oil disposal methods in the following categories:

- Burning in incinerators
- Dumping in sanitary landfills
- Solidification followed by dumping in sanitary landfills
- Landfarming
- Dumping into municipal sewers
- Indiscriminate dumping

No data exists to confirm the disposal of used oil in South Africa through some of the above stated disposal options.

2.4.1.a Burning in incinerators

Incinerators can be small or commercial burners used principally by municipalities for the disposal of solid wastes. Commercial hazardous waste incinerators are designed specifically for the destruction of hazardous materials and are equipped with the necessary pollution control equipment. ([3]CCME Report, 1989).

2.4.1.b Dumping in sanitary landfills

Landfill design does not incorporate the features necessary to protect the environment from used oil contaminants ([3]CCME Report, 1989). However, it is believed that large quantities of used oil have been deposited in landfills. Used oil can be incorporated in a stable solid matrix (using lime, fly ash, soil etc.) before being landfilled. This it is believed, will control potential leaching problems. However, the complexities and economics associated with the solidifying process render it unfeasible. ([3]CCME Report, 1989)

2.4.1.c Landfarming

Landfarming is a technique whereby hydrocarbon materials are applied to the soil and biologically degraded through microbial action. Landfarming experiments done on used lubricating oils ([3]CCME Report, 1989) show that used oil can have long-term negative effects on soil quality.

2.4.1.d Dumping into municipal sewers and indiscriminate dumping

A report by Rimkus, Lue-Hing and Lordi (1975) presents the effects of waste oils and greases on a municipal sewage treatment plant. The report shows that used oils dumped in sewers cause treatment problems in the sewage piping and aggravate maintenance and treatment problems on all sewage treatment plant equipment. When dumped indiscriminately all of the negative effects associated with used lubricating oils are exacerbated. ([3]CCME Report, 1989)

2.4.2 Burning to Utilise Energy Value

Used lubricating oils are burned primarily to utilise the oil's heating value. Other potential benefits from burning used oil as a fuel include ([4]CCME Report, 1989):

- Reduction in the consumption of non-renewable fossil fuels,
- Waste re-use by a method with potentially broad applications in industrialised regions,
- Provision of a re-use method with minimal waste by-product disposal requirements,
- Productive waste utilisation without need for the development of new technologies or large capital expenditures.

Used oil can be blended with virgin fuel oil before burning or can be burnt alone. It is typically burnt alone in small heating installations which have a ready supply of used oil. ([4]CCME Report, 1989)

When used to supplement virgin fuel oil, the two fuels are generally blended together prior to burning. Blending ratios are dependent on ([2]Used Oil Re-refining Hearing, 1977):

- Available supply of used oil,
- Ability of equipment to handle a fuel mixture with characteristics different to those for which it was originally designed,
- The tendency towards the build up of deposits,
- Local emission regulations.

Virgin fuel oils range from light distillates to heavy residuals. The American Society of Testing and Materials (ASTM) has developed standard specifications for fuel oils. Table 2.6 gives the grades and specifications for virgin fuel oils. Numbers 2 to 6 fuel oils are most frequently used. Virtually any burner designed for No. 6 fuel and most burners for No. 4 and No. 5 fuel oils can burn untreated used oils.([4]CCME Report, 1989) Table 2.7 gives a comparison of the properties and composition of virgin fuels to used lubricating oil fuel.

Table 2.6 Summary for specifications for fuel oils

	Fuel oil grades (number)					
Test procedures	1	2	4	5 (light)	5 (heavy)	6 (bunker)
Flash point (°C)	38 or *legal	38 or legal	55 or legal	55 or legal	55 or legal	60 or legal
Pour point (°C)	-18	-7	-7	--	--	--
Water & sediment (volume %)	0.05	0.05	0.50	1.00	1.00	2.00
Ash (weight %)	--	--	0.10	0.10	0.10	--
Kinematic viscosity (cSt) At 38 °C (100°F)						
Minimum	1.4	2.0	5.8	>26.4	>65	--
Maximum	2.2	3.6	26.4	65	194	--
Sulphur (weight %)	0.5 or legal	0.5 or legal	legal	legal	legal	legal

* "legal" refers to applicable laws or regulations setting maximum or minimum concentrations
Adopted from: [2]Used Oil Recycling Joint Hearing, 1980

Table 2.7 shows that used oil contains soluble and insoluble metallic compounds. The product from used oil burning, in most developed countries, must comply with particulate emission standards and regulations. The extent of environmental concerns associated with used oil burning will depend on concentration of hazardous contaminants in oil, burner design, emission control equipment, stack height, meteorological conditions, and the number of point sources within an area. (Franklin Associates, 1985;adopted from [4]CCME Report, 1989):

Table 2.7 Comparison of used automotive oil lubricants to virgin fuels.(adopted from [5]CCME Report,1989)

Parameter	100% Used Automotive Oil Lubricants	Virgin fuels: 100% Fuel Oil	Virgin fuels: 100% Coal
Gravity API @ 16°C	24.0	13.2	-
Viscosity (cm^2/S)	0.99	3.79	-
Pour point (°C)	2	-11	-
Flash Point (°C)	60	37	-
Heating Values (kJ/kg)	38 000	43 000	29 000
Bottom Solids & Water (Vol %)	11	1.0	-
Sulphur (wt %)	0.43	2.15	2.75
Ash (wt %)	1.01	0.25	10.5
Arsenic (ppm)	5	0.5	-
Barium (ppm)	48	3	258
Cadmium (ppm)	3	0.5	-
Calcium (ppm)	1850	48	7768
Chromium (ppm)	7	3	24
Copper (ppm)	177	1	64
Iron (ppm)	1025	120	14 467
Lead (ppm)	240	3	71
Magnesium (ppm)	559	14	1362
Phosphorus (ppm)	1250	-	30
Silver (ppm)	1	0.3	1.7
Tin (ppm)	58	-	225
Zinc (ppm)	480	1	123

Source:Rudolph,1978:PEDCO-Environmental Inc.,1984 & Franklin Associates Ltd.,1985

2.4.2.a Equipment in which used oil can be burnt

Currently, in Europe and America, untreated used oil is burned in (CONCAWE Report, 1996; McCabe and Newton, 1997):

- Space heaters
- Commercial and industrial boilers (also called industrial furnaces)
- Waste incinerators
- Cement kilns
- Electrical power generators

i. Space heaters

Space heaters are small combustion units with capacities less than about 400 000kJ/hr that are used to heat either air or water.([4]CCME Report, 1989) They are typically sold to service stations and maintenance shops of firms with large fleets of vehicles. Space heaters fire 3.8 to 7.6 lit/hr and are considered to be a reasonably efficient means of disposing used lubricating oils that are generated on site. The two principal designs for these systems are air atomisation and vaporising-pot heaters. (McCabe and Newton,1997)

The atomisation heater uses a nozzle and orifice to deliver the fuel into the combustion chamber in the form of a fine spray. Space heaters using the atomisation heater have been reported to promote relatively efficient combustion but emit 75 to 95 percent of the metals introduced in the flue gases. (McCabe and Newton,1997)

In vaporisation heaters oil is vaporised from a pan in the base of the combustion chamber. Low boiling organics are volatilised and burnt in the area directly above the pot, while metals and less volatile organic species are deposited as a slag at the base of the heater. The metals emission rate from these units is 5 to 15 percent of the metals fired. (McCabe and Newton, 1997)

ii. Boilers

A wide variety of boilers that fire used lubricating oils are available. The following use-categorised oil-fired boilers can be presented: ([4]CCME Report, 1989)

Domestic	Includes the generation of heat for space heating, cooking and other household operations at private house holds and farms
Commercial	Includes the generation of heat for space heating, water heating and cooking at non-manufacturing establishments such as apartment and office buildings, motels, restaurants, schools etc.
Industrial	Includes the generation of steam for space heating and/or process requirements at industrial establishments
Utility	Includes the generation of steam for the purpose of producing electricity

The design-based classification of boilers places them into three categories; water-tube, fire-tube and cast iron. However, of interest to us is not the boiler design but the burner type as this determines whether the boiler can fire used oil.

iii. Waste incinerators

Waste incinerators are normally used by municipalities as municipal waste incinerators or by waste management companies as chemical waste incinerators. Generally such waste incinerators do not accept bulk loads of used oil or any other material to be burned. However, if used oil is discarded amongst household waste, that oil would normally be incinerated with other household waste. Household waste is not incinerated in South Africa.

Waste incinerators burn a wide variety of wastes, for that reason there needs to be control of the quality and quantity of emissions leaving the waste incinerators.

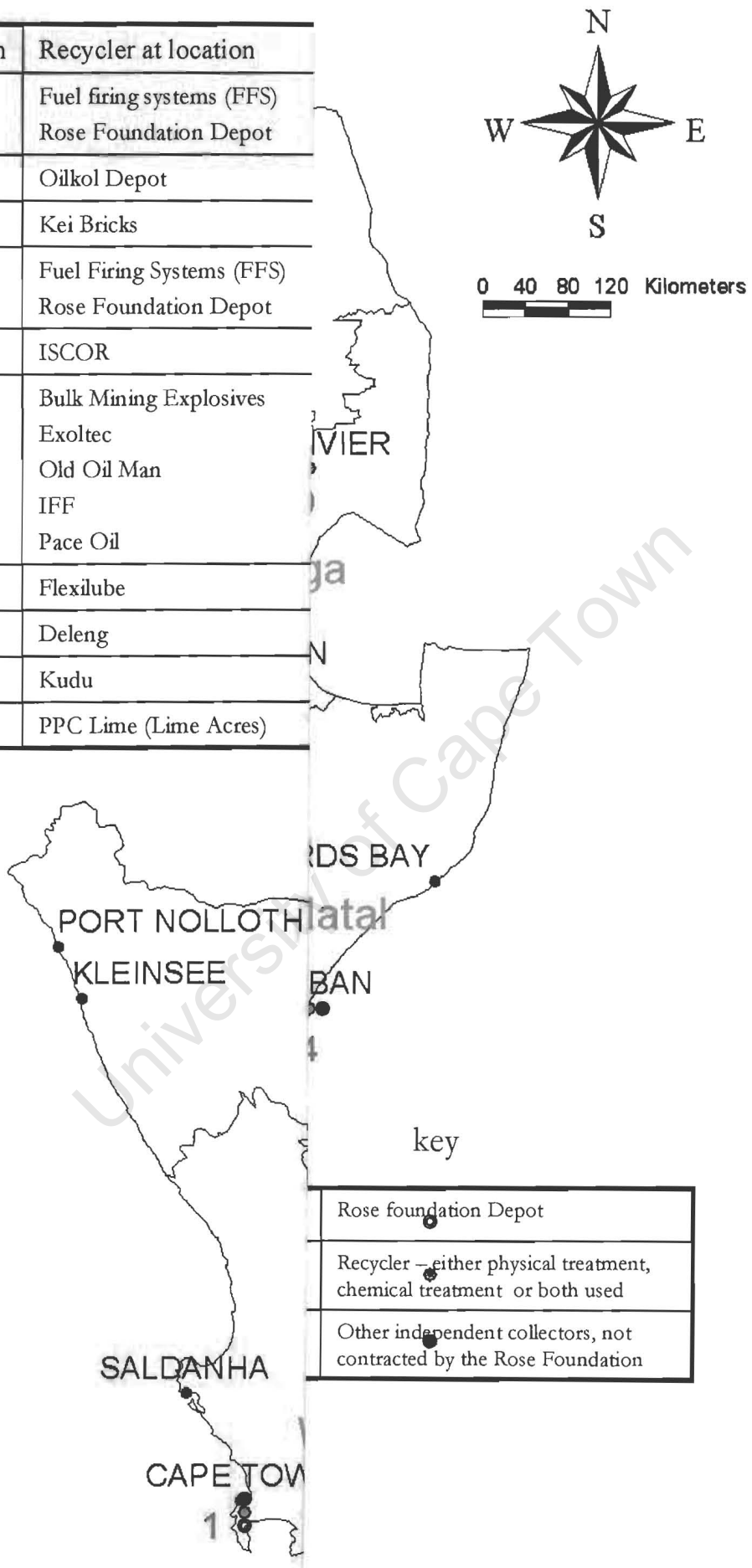
iv. Cement kilns

Cement is produced by combining limestone with silica, alumina, and iron oxide from clay. Two separate processes are used to produce cement, a wet process and a dry process. In the wet process, the ingredients are crushed and mixed with water to make a slurry which is about 40%. This slurry in pumped into a kiln. In the dry process, the ingredients are crushed, mixed, and delivered to the kiln in the dry state.

The kiln is of a large, horizontal, rotating type with a slope of 3° to 6°. Dimensions of a kiln are typically up to 250 metres in length and up to 8 metres in diameter. The kiln rotates between 50 and 70 revolutions per hour. The raw materials enter the high end of the kiln, and the fuel is introduced into the kiln at the low end. There are several distinct zones in the kiln, each having a

key

Position	Recycler at location
1	Fuel firing systems (FFS) Rose Foundation Depot
2	Oilkol Depot
3	Kei Bricks
4	Fuel Firing Systems (FFS) Rose Foundation Depot
5	ISCOR
6	Bulk Mining Explosives Exoltec Old Oil Man IFF Pace Oil
7	Flexilube
8	Deleng
9	Kudu
10	PPC Lime (Lime Acres)



key

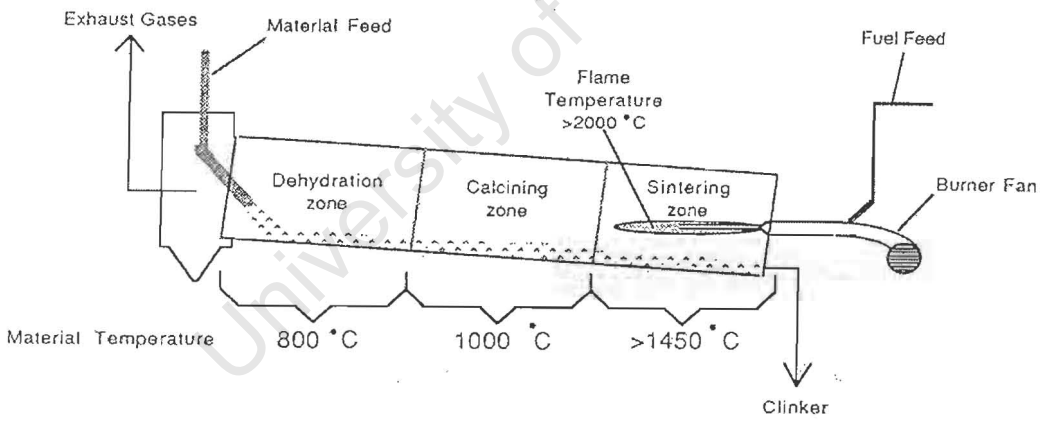
	Rose foundation Depot
	Recycler – either physical treatment, chemical treatment or both used
	Other independent collectors, not contracted by the Rose Foundation

characteristic temperature. (see Figure 2.1). The zones can be divided into the dehydrating zone, the calcining zone and the sintering zone. Reaction temperatures in the sintering zone reach at least 1450°C with a flame temperature of over 2000°C. Gas residence times are normally approximately 3 seconds. (McKendry-Smith, 1989)

The energy requirements of the process depend on the type and size of kiln being used, as well as on the type of cement being manufactured. The energy requirements range from 3700 kJ/kg cement produced for short kilns using the dry process and 6900 kJ/kg for long kilns using the wet process (Berry et al, 1975).

Kilns normally burn No. 6 fuel oil, natural gas or coal and can easily be modified to burn used oil. Used oil can be burned in cement kilns without many of the negative air quality effects normally associated with burning in smaller units. Investigators have determined that the hydraulic and structural properties of the cement would not be compromised by the use of waste oil fuels and that most of the oil contaminants would remain within the insoluble structure of the hydrated compounds in the concrete produced from the cement. ([4]CCME Report, 1989)

Berry et al (1975) also report that untreated used oil can be utilised as a fuel in cement kilns without adverse environmental impacts provided the kilns have adequate emission abatement facilities. The detailed results of the trials carried out by Berry et al (1975) on the dry process kiln at the St Lawrence Cement Company, Mississauga, Ontario indicate that most of the contaminants in the used oil are trapped in the cement product and in processing by products. The encapsulation of used oil contaminants in cement was found not to have any adverse effects on the cement quality.



Source: Mckendry-Smith, 1989

Fig 2.1 The cement kiln

v. Burning in asphalt plants

Used oils are used as fuel in asphalt plants. In the USA over 40% of the used oil burned in 1996 was burned in asphalt plants. These plants use emission control strategies ranging from wet scrubbers to baghouses. The used oil is burned untreated in furnaces within the plants. (McCabe and Newton, 1997)

vi. Direct burning options for used oil collected in South Africa

About 4 % of the total volume of used lubricating oil collected in South Africa is burned as a fuel without prior treatment in limekilns and brick making kilns. (Norton, 1999) No information was found which confirmed that used oils were being burned without prior treatment in heat recovery applications such as space heaters, industrial furnaces and cement kilns. Trials in which

used oil was as a fuel in lime kilns were carried out by PPC Lime in South Africa (Mozes, 1997) however the results of the trials were not made available for life cycle inventory building purposes. For this reason the results of the trials carried out by Berry et al (1975), in which untreated used oil was used as a fuel in the dry process kiln at the St. Lawrence Cement Company, Mississauga, Ontario were used in building a representative life cycle inventory in the research. It is recognised that the results of these trials are not directly applicable to South African cement or limekiln operations, but rather they form a basis for informing on the environmental performance that could be expected from burning used oil in cement kilns in South Africa.

2.4.2.b Problems Associated with Burning of Untreated Used Oils

i. Combustion problems

The most serious problems associated with the burning of used oil are related to the potential occurrence of combustion instability and the associated danger of explosion. To prevent this event from occurring it is recommended that used oils burned in furnaces have a flash point greater than the flash point set for the equivalent virgin fuel oil. (see Tables 2.5 and 2.6)

During combustion, used oil ash constituents form various metal oxides, which may be emitted from the stack as particulates or form corrosive deposits on the furnace walls and heat transfer surfaces.

The sedimentary material in waste oils is characteristically abrasive, leading to burner nozzle tip erosion and damage of pump seals. Generally re-refiners have experienced low durability of pumps used for the transportation of oil in the plant. Another problem related to the combustion of used oil is the high water content of untreated used oil, which can result in a number of undesirable conditions, including fuel line freezing in cold weather operation, aggravated heat release fluctuations, and flame out, particularly in smaller units. ([4]Used Oil Re-refining hearing, 1977)

ii. Environmental considerations

Particulate size in the flue gases is determined by the reactions of the used oil ash constituents during combustion and subsequent secondary reactions between the ash particles formed and the gas stream. Particulate size distributions for the six predominant particulates emitted during the combustion of used oil are listed in Table 2.8. The particulates formed in the combustion process are emitted in the stack or retained within the boiler.

Table 2.8 Particle size distribution of lead and other contaminants in emissions from waste oil combustion

	Weight percent					
Particle size	Lead	calcium	phosphorous	zinc	iron	barium
<1 micron	69-76	10-19	23-42	56-73	2.7-36	3.3-51
1 to 10 micron	16-21	71-74	49-66	23-39	51-80	40-79
>10 micron	2.7-4.4	10-15	8.9-10	3.4-5.0	13-18	8.9-18

Source: ([4]Used Oil Re-refining hearing, 1977)

Of all the trace metal particulates emitted, lead is of principal concern with regard to health effects. In addition to particulates and trace metal emissions, there is concern relative to the emission of polynuclear aromatics (PNAs) and PCBs. These require high temperatures for complete destruction and are also of concern for health reasons.

The environmental risks associated with burning of untreated used oils in any size burner can be reduced through the application of a variety of management strategies. Possible options include:

- Pretreatment of used oil to meet quality specifications (e.g., settling, centrifugation, vacuum distillation, solvent extraction) – see section 2.4.3
- Dilution of used oil contaminants by blending with virgin fuel oils or co-firing with coal
- Installation of flue gas emission control equipment
- Implementation of a program incorporating various combinations of the above options

2.4.3 Reprocessing for Re-use and Subsequent Burning

Industrial processes generally require less strenuous lubricating applications when compared to automotive lubrication. The used oils from industrial oils, if properly segregated may be cleaned by simple processes such as heating to evaporate moisture and filtration. This is also called reprocessing or reclaiming the waste oils. The clean oils may be re-employed in their industrial applications. The type and extent of reprocessing employed depend on the extent of contamination of the industrial oil. (Pyziak and Brinkman, 1993)

Simple filtration methods are used for reprocessing hydraulic fluids that are relatively clean. Walters (1975) reports on a system for the severe reprocessing of waste hydraulic oil using filtration, vacuum dehydration and optional clay contacting.

Waste oils are also reprocessed for other uses that do not require the adherence to the highest standards of performance from the lubricant. Cutting oils are being recovered by methods employing gravity, thermal drying, chemical cleaning and wringlers. (Oliverson, 1975) A waste locomotive engine crankcase oil reclamation system used on several rail systems involves dehydration, coagulant addition and/or filtration prior to re-use in locomotive engines. Waste oils may also be reclaimed and marketed as API/SA motor oil. (Pyziak and Brinkman, 1993) Filtration of oil from the head end gearboxes on spinning machines is done to remove impurities and to permit the oil to be re-used. (Walters, 1975)

Used oils are also reprocessed for use as industrial fuels. Owing to the numerous environmental hazards and equipment maintenance problems associated with burning untreated used oils, specifications have been set for the burning of treated used oil. Table 2.9 gives the used fuel oil specifications set by the EPA in the USA. Waste oils meeting these criteria may be burned in burners of any size without regulation, since these specifications have been determined to be protective under virtually all circumstances and fuels meeting them should not produce adverse environmental impacts. These specifications are generally equivalent to worst-case levels found in virgin fuel oils. (McCabe and Newton, 1997)

The extent of processing of used oil to a specification fuel is determined by the specifications of the oil desired by the end user. At the highest quality the oil is reprocessed to meet the specifications of virgin fuel oils, this process in then called re-refining and will be discussed in section 2.4.5 of the chapter. However, additional treatment costs involved and the marginal benefits associated with these treatment steps generally place high quality specification fuel at a disadvantage to virgin fuel oils.

Treatment steps for used oil fuels are kept minimal in order to maintain the significant cost advantage over virgin fuels. Basic treatment steps such as settling, filtration and dehydration are used to produce a fuel, which can be readily fired in most burners. However, the physical

treatment does not address the presence of chemical contaminants in the oil. Also, some of the physical treatment methods depending on extent of treatment do not effectively remove particles of an extremely small size. As discussed above, the specification criteria for the used oil fuel generally relate to considerations such as heat content, viscosity, flash point and bottom sediments and water (BS&W).

Table 2.9 Used-Oil-Fuel specifications

Constituent or property	Allowable level
Arsenic	5 mg/kg maximum
Cadmium	2 mg/kg maximum
Chromium	10 mg/kg maximum
Lead	100 mg/kg maximum
PCBs	2 mg/kg maximum
Total halogens	4000 mg/kg maximum
Flashpoint	37.7°C (100°F) minimum

Source: Federal Register, vol. 50, No. 23, 49, 164-49, 249 and 40 CFR Part 271
Adopted from: McCabe & Newton, 1997
Note: mg/kg equivalent to ppm (parts per million)

More intensive treatment processes such as centrifugation, clay contacting and distillation may be used to address the problems of a greater range of contaminants. This processing constitutes what may be termed "severe" reprocessing and transforms the used oils into fuels that can be burned with similar emissions to those from burning other fuel oils. As discussed earlier Table 2.6 gives the grades and specifications of virgin fuels, which form the target specifications for the severe reprocessing, used oil treatment. (CONCAWE Report, 1996)

About 76 % of the volume of used oil collected in South Africa is reprocessed for subsequent burning. (Norton, 1999) Companies operating reprocessing plants include FFS Refiners and Exoltech. These treatment plants produce a low sulphur fuel which is normally blended with heavy fuel oil and subsequently burned in a variety of industrial applications. These include brick making kilns, commercial and industrial boilers, and direct firing industrial furnaces. The burning of reprocessed oil in a brick-making tunnel kiln and in an industrial furnace are two specific used oil management options that were proposed for analysis in the LCA representing processes burning reprocessed oil in South Africa.

When burning used oil in the brick-making tunnel kiln, the fuel as well as the products of combustion come into direct contact with the material being heated or processed, allowing for reactions which may immobilise some of the contaminants that are in the reprocessed oil. In industrial furnaces neither the fuel nor the combustion products come into direct contact with the material being heated or processed and the factors affecting the flue gas composition include the burner section design, the furnace firing temperature and the amount of excess air in the combustion zone (Basu et al, 1999).

2.4.4 Re-use or Downcycling Options

Re-use or downcycling options for used oil management will be classified as those options in which the used oil is used as a substitute or a supplement in an application that does not demand stringent performance specifications. For this reason downcycling options will normally exclude used oil burning or lubricant applications. In this section some downcycling options utilising both treated and untreated used oils will be discussed.

2.4.4.a Some downcycling options for untreated used oil

i. Road Oiling for Dust Control

The use of used lubricating oil in road oiling has been practised widely in North America. (USA and Canada) SAE Report No. 740684 (1974) reports that in 1974, 120 million gallons of waste crankcase oil (40% of all waste crankcase oil recovered in USA) were used for road oiling. However, the Used Oil Recycling Act of 1980 has severely restricted if not totally discouraged the road oiling practice after used lubricating oils were classified a hazardous waste. (Beiring, 1993) Road oiling is now illegal in most states in the USA. (Pyziak and Brinkman, 1993) Irwin (1978) reports that used oil applied as a dust suppressant has been found to contain toxic or carcinogenic contaminants such as 2,3,7,8-tetrachlorodibenzodioxin, polychlorinated biphenyls and 2,4,5-trichlorophenol.

Studies have been carried out to investigate the fate of used oil after road oiling.(Freestone, 1972; Bell, 1976; Stephens et al, 1981; Surprenant et al, 1983; quoted in [4]CCME Report, 1989) The results of these studies agree that used oil applied as a dust suppressant is lost through; volatization, vehicle adhesion, biodegradation, wind entrainment of dust particles and as runoff with rain water. There is also agreement that the relative quantities lost by each of the above methods is not uniform but depends on factors such as soil type, traffic density and climatic conditions.

Norton (1999) reports that used oils are employed, in South Africa, in road oiling for dust control. However, the volume of used oil consumed, in South Africa through this re-use option is not quantified and their impact on the environment has not been investigated.

ii. Wood pole oiling

Wood poles are used extensively on electrical and telephone transmission lines as well as fencing poles. In these conditions the poles are exposed to almost every soil and environmental condition imaginable, as well as to possible attack from biological degraders such as termites. Wood pole oiling is carried out to increase the durability of the wood poles in a given serve by protecting the wood the above stated destructive elements. (Cox Industries Inc., 1999)

Wood pole oiling however, releases the used oil directly to the environment through evaporation, rain and ground water dissolution. Norton (1999) also reports that used oil is used in wood pole oiling in South Africa but no information is available on the quantities consumed.

2.4.4.b Some downcycling options for treated used oil

i. Manufacture of explosives

About 9% of the used oil volume collected in South Africa is reprocessed for use in the manufacture of slurry explosives. (Norton, 1999) No data is available on the environmental consequences of using reprocessed oils in the manufacture of explosives and this option has not been considered as an alternative used oil management option in the comparative environmental analysis of used oil management options in South Africa.

2.4.5 Re-refining of Used Lubricating Oils

2.4.5.a The purpose of re-refining

In re-refining the used oil is treated until it meets physical and chemical specifications equivalent to those of virgin base oils. There are many characteristics that are desirable in a lubricating base stock. These include:

• Solvency	The ability of base oil to solubilise various chemical additives and oxidation products
• Oxidation Stability	Stability of the base oil under oxidation conditions
• Additive Response	The extent of improvement in oxidation, corrosion and wear characteristics from additives
• Thermal stability	Stability of the base oil against high temperature degradation in the absence of oxygen
• Low temperature fluidity	The ability of the base oil to maintain fluidity under low temperatures
• Oil consumption	The ability of the base oil to avoid excessive volatilisation under normal operating conditions

(Hsu, 1980)

There are number of advantages to re-refining. Depending on the efficiency of the management policies in place the justification for re-refining may be economic, strategic and/or environmental.

Economic

For most countries lubricating oil is produced in the main from imported raw materials. Its manufacture requires the use of high technology methods of refining and considerable expenditure in chemical materials. It is thus argued that no country can afford to dispose of such a valuable product after using it only once. (Chatwin, 1975) Moreover, Hakes et al (1997) report that in an efficient re-refining process 2.5 gallons of used oil will yield one gallon of re-refined oil. In contrast, it takes 84 gallons of crude oil to produce 1 gallon of motor oil. This clearly represents huge savings on a non-renewable resource. In addition to this the construction and operation of a re-refining plant is much less costly compared to a crude oil refining plant.

Strategic

Twentieth century history has shown the need and importance of a strategic national emergency oil reserve. A paper presented to the [5]Used Oil Re-refining Hearing (section 12, 1977) in the USA recommends that should there be a sudden surge in domestic demand, as for military action, an extra capacity for re-refining (if available) could supply the shortfall. A similar but more drastic situation would be interruption of foreign oil supplies for an extended time period. In that event, the re-refining industry could play a major role in the production of lube oils for transportation and industrial applications. ([5]Used Oil Re-refining Hearing, 1977) The Middle East War of the early seventies resulted in the disruption of crude oil supplies. In the lubricating oil trade there was considerable disruption and, for a time, a shortage. (Chatwin, 1975)

Environmental

Used oil presents a multitude of potential dangers to the environment and to health if disposed of by unauthorised tipping. Used oil contains poisonous and contaminating wastes, which are properly treated during the re-refining process. Re-refining also prevents the direct dumping of the base oil into the environment and reduces the potential pollution from burning used oil. (Beiring, 1993; Chatwin, 1975; CONCAWE Report, 1996)

A number of studies have been commissioned, many of them using LCA, to verify the perceived superiority of used oil re-refining options when compared to other used oil management options, in particular burning for energy recovery. The details and findings of some of these studies are presented in section 2.7 of the chapter.

The main focus of re-refining technology evolution has been on used automotive oils. This is the principal large volume source. The impurities to be removed have a certain amount of consistency, despite diverse lube additive formulation technologies. Additives and fuel lubricant decomposition products make processing quite complex. Many industrial lubricants can be accepted as part of the feed without encountering problems such as hydro-finishing catalyst poisoning or downgrading of viscosity index. (McKeagan, 1992)

2.4.5.b Quality concerns in re-refining of used lubricating oil

At the heart of the interaction of the automotive and oil industries is the joint concern about responsibility for acceptable engine performance or the occasional engine failure. To avoid the latter there has been co-operation in technical progress concerning the automobile engine. The Society for Automotive Engineers (SAE), the American Petroleum Institute (API) and the American Society for Testing and Materials (ASTM) have jointly established performance limits for engine oils, called "engine sequence tests" ([6]Ball et al, 1977).
Re-refined base oils are also tested to these stringent testing standards set for virgin lubricants. In particular, the American National Bureau of Standards (NBS) was tasked with responsibility of developing and evaluating test procedures for establishing the substantial equivalency between re-refined and virgin petroleum oils.

A re-refined oil has to pass a series of ASTM tests and comply with performance requirements of US Army MIL-L-46152 and API Service SE/CC quality. ([1]Ball et al, 1977) The USA department of defence has put considerable effort into revising the military petroleum product specifications to allow the use of recycled or re-refined materials. (Bowen, 1980) Advances in re-refining technologies and processes have characteristically targeted that their product meets the MIL-L-46152 specifications.

The Association of Petroleum Re-refiners (APR) also promulgated a set of standards or specifications for re-refined base oils which could be in some way used for requirement for active membership. The specifications written were for SAE, 10, 20, 30, and 40 grades and included viscosity limits, flash points and maximum colours. These standards were put together in 1950 and were first revised in 1961. In 1977 the directors of API requested the further revision of the standards. This continuous upgrading of standards has been necessitated by the ever-increasing performance demands put on automotive lubricants by engines. (Pedall, 1980)

2.4.5.c Extent of used oil re-refining in selected countries

According to the CONCAWE Report (1996) at the time of publication there were around 400 re-refining facilities around the world with an overall refining capacity of 1800 kt/year. The extent of re-refining relative to quantity of collected base oils for selected European countries, as given in the CONCAWE Report (1996) is presented in Table 2.10. However the share of re-refined oils accounted for less than 10 % of the overall base oil demand in Europe.

The numerical data presented in Table 2.10 on total base oil sales, volumes of used oil collected and percentage of collected oil re-refined in selected European countries indicate the following trends:

- In general countries with large sales of base oils and in relation larger volumes of collected used oil have some re-refining operations processing a significant proportion of the collected used oil.

- Countries collecting less than 100kt/yr do not have re-refining operations. An exception is Greece which was importing 18kt/yr of used oil to supplement a processing throughput of 20kt/yr on its 30kt/yr capacity LPC Hellas re-refining plant.

Table 2.10 Relationships between lubricating base oil sales and used oil re-refining volumes in selected European countries

Country/Region	Total sales (ktonnes)	Used oil collected (ktonnes)	Mass re-refined (ktonnes)	% of collected Re-refined
Europe	4869	1312	420	32
Austria	86	24	--	--
Belgium	219	48	0	0
Denmark	78	32	0	0
Finland	93	27	0	0
France	891	206	86	42
Germany	1165	400	165	41
Greece	122	*33 (15+18)	20	61
Ireland	40	7.5	--	--
Italy	780	170	137	81
Netherlands	275	65	0	0
Norway	82.7	31	0	0
Spain	358	96	12	12.5
United Kingdom	806	199	0	0

* 18kt are imported
Source: adopted from CONCAWE Report data, 1996

One can conclude from these observations that re-refining, where the collection capacity is permissible, is a widely used oil management option in Europe. The draft European Union Waste Oil Directive, 1998 proposes the strengthening of the priority for re-refining over burning with energy recovery (Davies, 2000) and some European countries such as Italy already use a policy that re-refining is the best available option as regards environmental compatibility in used oil management. (ENI, 2000) In South Africa about 11 % of the total volume of collected used oil is re-refined. The data given in Table 2.10 confirms that re-refining is an important used oil management option and for this reason it will be considered in the LCA on used oil management scenarios in South Africa.

2.5 TREATMENT PROCESSES APPLIED IN RE-REFINING

Designers of re-refining technologies have to set their standards on the requirements of the various afore-mentioned institutions. In an effort to produce a high quality lubricating base oil, commercial re-refiners have used a combination of two or more of the following technologies:

- Dehydration
- Settling and centrifugation
- Solvent treating or solvent extraction
- Vacuum distillation
- Hydrogenation/hydro-treating

2.5.1 Dehydration

Virtually all re-refining processes start with a dehydration (distillation) step to remove water and light ends (the fuel fraction) from the feedstock. The collected used oil is first pumped into a flash dehydrator (this may also be called a dewatering column or a dewatering tower), which uses a partial vacuum and an elevated temperature to evaporate the bound water and light hydrocarbons. Dehydration is a pre-treating stage in the re-refining process and cannot in itself produce an oil quality substantially equivalent to virgin base oil. ([7,8]Used Oil Re-refining Hearing, 1977)

2.5.2 Settling, Filtration and Centrifugation

Settling, filtration, centrifugation and the above-discussed dehydration are treatment processes normally applied in used oil reprocessing or reclaiming. Although all pre-treatment processes are physical processes, dehydration removes liquid contaminants in the oil while settling, filtration and centrifugation are used to segregate the liquid oil component from the solid sludge contaminants in the oil.

Settling is the simplest of the pre-treatment processes as it only requires a settling tank, which may operate with heating or at ambient temperature. The oil and the contaminants (liquids and solids) separate out over time because of density differences and are collected separately.

Almost every re-refining process uses filtration equipment. (Allen, 1976) The type and efficiency of the filtration equipment depends on the particle size and type of contaminants to be filtered. At the beginning of the re-refining process dirty oil may be pumped through filters where large size solid contaminants are retained. If the particles are of a relatively small size, vacuum filtration may be employed. Some re-fining processes such as the acid/clay process use solid materials in the treatment process. Subsequent to the large-scale clay treatment, high vacuum filtration is employed to separate the oil from the clay. Cartridge filters and Fuller's earth filters are frequently used in the re-refining industry. (Oliverson, 1975; Walters, 1975)

The centrifugal principle of separation of substances is based on the knowledge that any two substances with different specific gravities, not soluble in each other, can be separated by gravity. Centrifugation employs a force many times greater than natural gravity and can quickly and completely separate particles of a very small size form used oils. However, centrifugation has little or no effect on lubricant additives because the specific gravities of additives are close to those of oils.

Standard industrial centrifugal bowls are equipped with a series of conical discs that divide the contaminated lubricants into layers not more than 1mm thick. The used lubricant is fed through the top inlet and travels down the inlet tube into the centrifugal bowl. As the feed material (oil, water and solids) is forced upwards through holes in intermediate discs and spaces between the discs, the centrifugal action separates the material into heavy and light phases. (Allen, 1976)

2.5.3 Chemical Treatment

Chemical treatment of used oil in re-refining involves the addition of chemicals to the oil that react with the contaminants in the oil so that the reaction product is in a state easier to separate by physical treatment. Chemicals used include sulphuric acid, diammonium phosphate, aluminium salts and phosphoric acid. Chemical treatment is used to remove metals from the oils. The product from all chemical treatment processes however, is oil with a wide boiling range and the oil product is normally taken through fractional distillation or distillation hydrotreating. (Al-Ahmad and Al-Mutaz, 1991)

Chemical treatment is used, for example, in the acid clay treatment process where concentrated sulphuric acid is added to the oil. An acidic sludge composed mainly of metallic products is formed. ([7,8]Used oil re-refining hearing, 1977)
In the PROP re-refining process, which is to be described in Table 2.11, diammonium phosphate is added to the waste oil which is not dehydrated. A large proportion of the contaminants undergo metalisation reactions.(Muller, 1984) Tarrer and associates (1989) carried out experiments on the demetallation of used oils using the metallic borohydrides ($NaBH_4$ and KBH_4) and diammonium phosphate. These chemical demetallation agents were used to convert entrained non-filterable metals to a form that could be effectively removed by filtration. (Tarrer et al, 1989)

2.5.4 Vacuum Distillation

Distillation takes advantage of the difference in boiling points of chemical compounds. (Lee and Gentry, 1997) In a refining plant lube base oil is produced from crude oil using the combination of atmospheric distillation and vacuum distillation. Typically vacuum distillation separates the lube base oil into the various cuts. (Sequeira, 1989)

Vacuum distillation is also used in treating used lube oils where it performs the combined function of separating the lube oil from the heavy ends and generating multiple product streams. Vacuum distillation completely separates the oil from any trace metal or solid compounds that are untreatable using filtration and centrifugation. The bottoms from the process may be used as asphalt extenders or as fuel for industrial furnaces (Brinkman, 1989)

2.5.5 Solvent Extraction

Many solvents are used for the treatment of used oil, for example methyl ketone, butanol, propanol, iso-propanol, propane, tetrahydrofurfuryl and supercritical ethane. Commercial plants usually have combinations of treatment methods in different orders and degrees of complexity. Solvent extraction is normally used in combination with fractional distillation, decolorisation and deodorising plants (Al-Ahmad and Al-Mutaz, 1991).

If a solvent is designed to recover the base oil, separating it from the additives and particulate matter, the solvent must have the following properties:

- It must be miscible with the base oil contained in the waste oil being processed,
- When mixed with the waste oil, it must reject from the solution the additives and the dispersed particles (or part of them), allowing their aggregation to particle sizes big enough to separate from the liquid by sedimentation.

When a liquid meets the two requirements it may be called an extraction-flocculation solvent. (Alves dos Reis and Jeronimo, 1988)

In re-refining processes using solvent extraction dehydrated oil is contacted with the solvent in a solvent extraction unit. The flocculated sludges are collected as residue while the base oil-solvent solution is sent to a thermal-stripping unit where the solvent is recovered and recycled. (CONCAWE Report, 1996)

2.5.6 Hydrogenation/Hydrotreating

The finishing process, catalytic hydrogenation, for used lubricating oils is similar to that used by virgin crude manufacturing facilities. It removes most sulphur, oxygen and nitrogen from the base oil. This addition of hydrogen also eliminates most of the compounds causing colour, odour, and/or autoxidation, while significantly reducing the concentration of polynuclear aromatics (PNAs). (Pyziak and Brinkman, 1993)

In a catalytic hydrogenation unit the feedstock is heated to reaction temperature, mixed with hydrogen under pressure and passed down flow through a series of catalyst beds. Hydrogen quench is used between the beds of catalysts to remove heat generated by the exothermic reactions and control reaction temperature. The product from the reactor passes is separated at atmospheric pressure and the hydrogen is recovered and recycled. (²Sequeira, 1994)

The hydrogenation finishing process treats the base oils by purification, saturation and cracking. Figure 2.2 gives some of the possible reactions during the treating process.

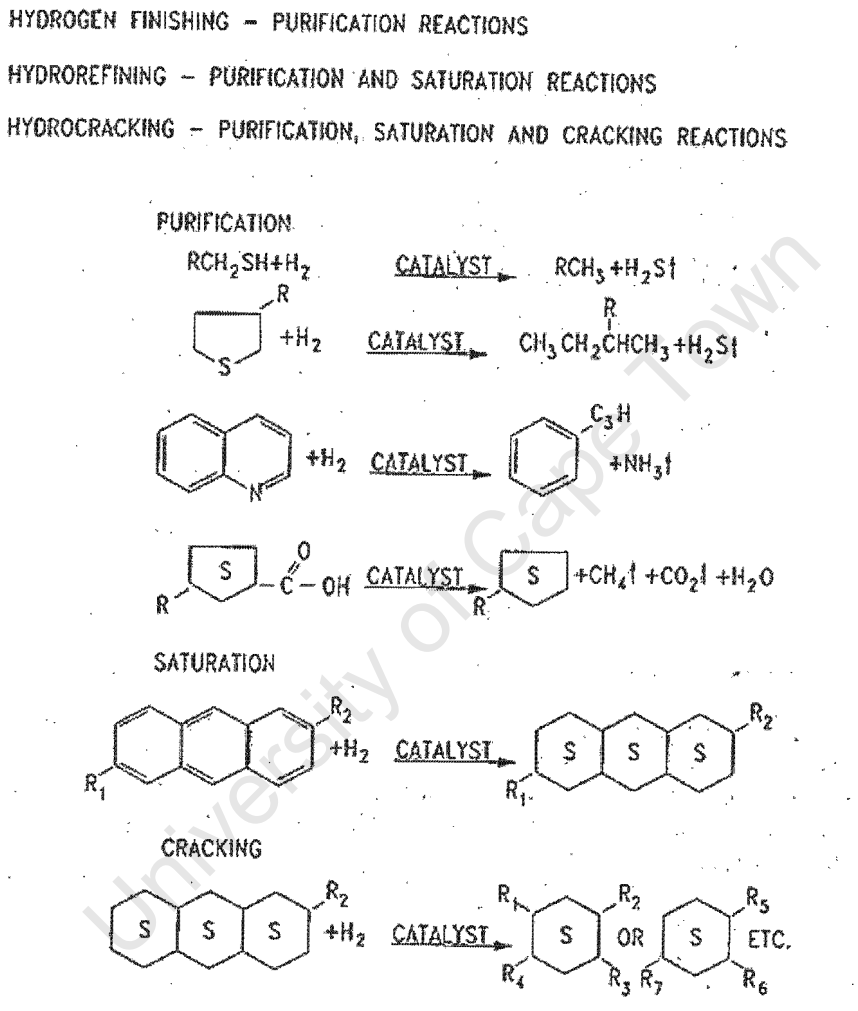


Figure 2.2 Chemical reactions of hydrotreating processes
*S = saturated ring
Source: Lubricant Base Oil Processing, ²Sequeira (1994)

2.6 TECHNOLOGIES EMPLOYED IN PROCESSING USED LUBRICATING OIL

2.6.1 Technologies for Reprocessing Used Lubricating Oils

Many companies have designed used oil reprocessing and/or reclaiming schemes over the years. Some are patented units while others are constructed from salvaged refinery equipment. Allen (1976) reports on a compact oil reclamation unit made by Allen Filters Inc. The oil reclamation units are relatively compact and are sold as package systems, completely assembled on their own foundations. The systems can be fully automated and are capable of operating at a flow rate of 460 litres per hour.

Oliverson (1975) describes three types of reclaiming systems of varying degrees of complexity that are used to recycle industrial oils. These plants are relatively small and compact as to allow in-plant reclamation of used industrial oils and for use by small capacity operators processing less than 30 000 litres per eight-hour shift. To show the diversity of reprocessing equipment available, Oliverson (1975) provides a list of more than 20 oil reclamation equipment manufacturers.

Walters (1975) of the Eastman Kodak Company reported on the operation of a waste hydraulic oil reclamation plant. Of interest however are patented units capable of processing significant volumes of used oils. To be described individually are the Revivoil Reprocessing configuration, the Vaxon process and the Trailblazer Process. The Revivoil Reprocessing configuration will be used as a representative reprocessing technology in the LCA.

2.6.1.a The Revivoil Reprocessing configuration

The Revivoil Re-refining process can be presented in a simplified version of the thermal deasphalting process without any second stage and can produce a demetalized product suitable as an industrial or marine diesel fuel. This demetalized product can also be used in other applications that can utilise reprocessed oil. (Giovanna et al, 1999)

2.6.1.b The Vaxon Process

The Vaxon used oil treatment process was developed by ENPROTEC. It consists of a series of vacuum cyclone evaporators followed by the chemical treatment of distillates obtained. In the Vaxon process the first stage removes water, naphtha and light ends. The second stage removes gas oil and spindle oil from the bulk of waste oil. The third and fourth stages separate different distillate cuts from the residue in which all the metals, additives and degradation products are concentrated.

The resultant distillates are then available as a good quality industrial fuel. This process can also be extended to create re-refined base oils.
(CONCAWE Report, 1996)

2.6.1.c The Trailblazer Process

The Trailblazer process was developed and patented by Texaco Inc. In this process the used oil is dehydrated in a flash tower, heat soaked and then processed by vacuum distillation to produce three product streams.

- The first stream consists of light hydrocarbons consisting of gasoline, kerosene etc.

- The process produces vacuum distillates that comprise of ash-free hydrocarbons in the diesel range. The vacuum distillates meet fuel oil specifications for several applications, including marine diesel oil.

- The bottoms from the vacuum distillation unit form an asphalt extender. The asphalt extender encapsulates the metals, additives and the degradation products.

The process produces a fuel oil product that can be burned without harmful emissions to the atmosphere.

A plant with a capacity of 150kt/yr of used oil is in operation in Louisiana, USA. The process produces an ash-free distillate oil yield of 80% on a dry basis. (CONCAWE Report, 1996)

2.6.2 Technologies for Re-refining of Used Lubricating Oil

Many technologies have been developed for re-refining and are in operation on an industrial scale. Re-refined lubricating base oils have to meet the strict performance standards set for virgin lubricating base oils and a number of companies have engaged in efforts to re-refine used lubricating oils. Technologies most widely accepted and utilised around the world are briefly described individually in Tables 2.11a and 2.11b.

The volume of used oil collected in South Africa that is re-refined, is processed in an acid-clay treatment re-refining process operated by a company called Flexilube based in Meyerton. No attempt was made to gather data on the operation, because the acid clay re-refining process is not viewed to be representative of the best available technology as it generates larges quantities of hazardous, acidic solid waste. There are however, many re-refining technologies available elsewhere that could be used for re-refining used lubricating oil collected in South Africa. The Revivoil process designed with the technical cooperation of the Institut Francais du Petrole (IFP) and Viscolube Italiana Spa was selected as a representative re-refining technology for purposes of building life cycle inventory data modules for the re-refining management option. Revivoil has two configurations to its re-refining plant; a lower base oil yield process consisting of a preflash, thermal deasphalting (vacuum distillation) and a catalytic hydrofinishing unit. The high yield configuration applies a solvent extraction, Propane Deasphalting (PDA) stage onto the bottoms product to the thermal deasphalting stage, and the PDA product is also taken through the catalytic hydrofinishing process.

2.6.3 Re-refining Technologies that are Under Development

Around the world there are many activities to improve the existing used oil technologies and to develop new ones. Examples are The UOP Re-refining Technology, the ENTRA technology and Supercritical Extraction. The CONCAWE Report (1996) gives a brief description of technologies under development.

Table 2.11.a A Summary of the most wide

Meinken Engineering Acid/Clay treatment Pr

In this process, used oil is first pumped into a flash dehydrator w
The dehydrated oil is then cooled to 38°C and transferred to a
allowed to settle. Temperatures of 38°C are maintained in the set

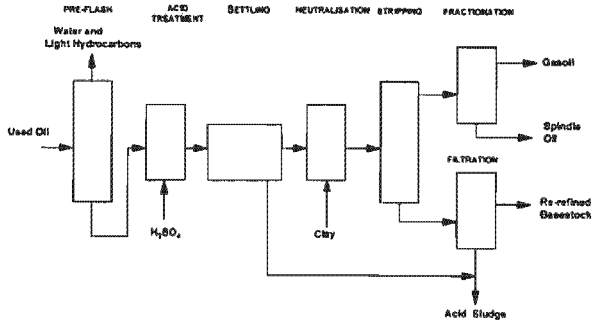
The sludge, containing unreacted acid and most of the used oil c
is introduced to remove acidic and malodorous compounds, and

Heating is discontinued and about 25 to 75 kg of activated clay
stripping and clay contacting are finishing steps.

The resulting base stock is a neutral solvent base stock which is t
(*US Used Oil Re-refining Hearing, 1977*)

The advantages of the acid /clay treatment process are the rela
declared by Mienken is 63% on a dry basis. (*CONCAWE Report*)
The greatest disadvantage with the acid clay process is that it pr
more environmental problems than the waste oil itself. It is diffic

The quality of base oil produced has been broadly acceptable
environmental impact of the by-product (acid sludge and clay). (



The Distillation/Chemical Treatment Process

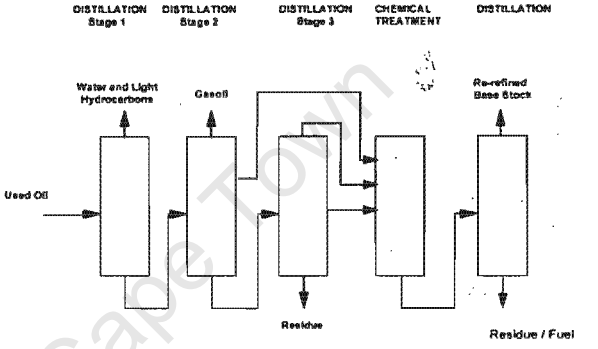
The distillation/chemical treatment process was developed by E

The process consists of a series of vacuum cyclone evaporators,

- The first stage in the process removes water, naphtha and l
- The second stage removes the gas oil, spindle oil or light fu
- The third and fourth stages separate different lubricating o

Chemical treatment is carried out in blocked operation, followed

An alternative solvent extraction stage can be used whereby virtu
A plant designed using this process is in operation in Spain and
(*CONCAWE Report, 1996*)



The Propane Deasphalting (PDA) Process

The Propane Deasphalting technology employs liquid propane

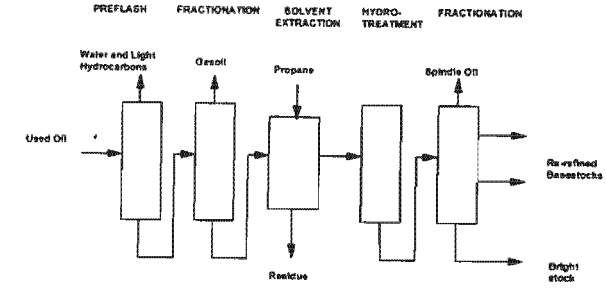
The first stage of the process is the pre-flash, where water, light

In the second stage the asphalt is separated from base oil by extr

Single stage extraction (PDA-IFP Process)

In the single stage PDA extraction unit, the clarified oil is separa

IFP was the first company to employ this technology and it is us



Two stage extraction (Snamprogetti Proce

In the two-stage extraction process the clarified oil coming fro
the first PDA unit.

The oil cuts coming from the side cuts of the vacuum column,
Petroli) in Italy.

The two-stage process, compared to the single stage, provides a
(*CONCAWE Report, 1996*)

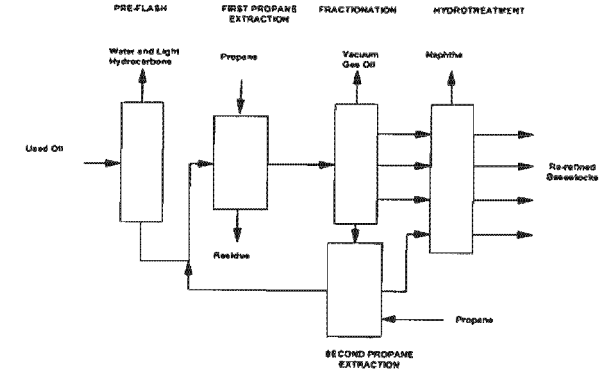


Table 2.11.b A summary of the most wi

The Thin Film Evaporator (TFE) and Hydrot

The Thin film evaporator and hydrotreating process is employe

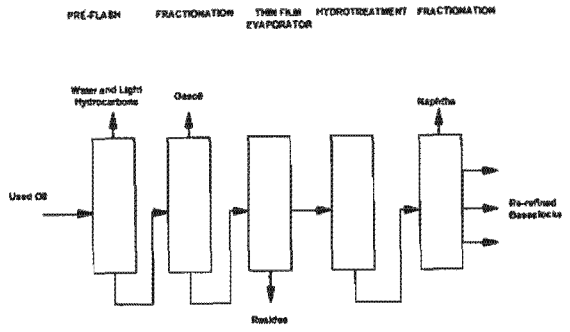
The first stage of treatment in this process consists of a pre-fl
CEP case a chemical treatment step is also included to minimis

Deasphalting is performed by the TFE, hot oil heated, operatin

After hydrotreating, the lubricating oil fraction is separated into
(*CONCAWE Report, 1996*)

One prime attraction of the TFE is that it can be retrofitted
necessary to prevent coking in more traditional fractionating
encounters with several product and reflux streams in a tower.

A principal disadvantage is the need for several units, or the ne
Entrainment of higher boiling components in the vapour phase



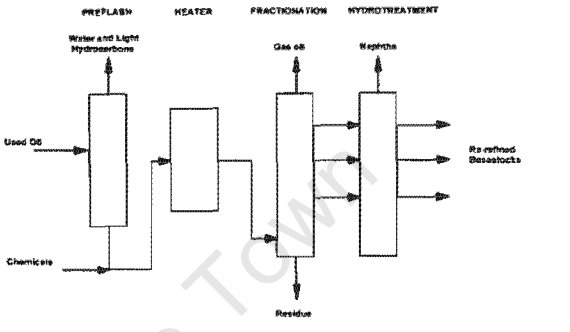
The Thermal Deasphalting (TDA) Process

The Thermal Deasphalting of residue (TDA) technology has be

The process consists of a pre-flash where the water, light ends a

The pre-flash oil is partially deasphalted by settling it in a specia

Finishing is accomplished either by clay treatment or by hydrot
(*CONCAWE Report, 1996*)

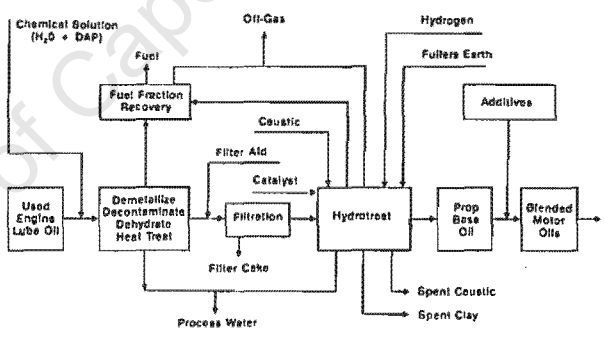


The PROP Re-refining Process

The Phillips Petroleum Company of Bartlesville, Oklahoma des

In the PROP Process the typical dehydration/fuel stripping i
combines with other contaminants to form a sludge, which is fi
After the demetallisation stage the oil is hydrotreated. (*Brinkma*

The disadvantages of the basic system are the lack of a distillati
PROP process incorporated distillation units to alleviate these
Without any extra hardware the PROP Process is usually consid
(*Brinkman, 1987*)

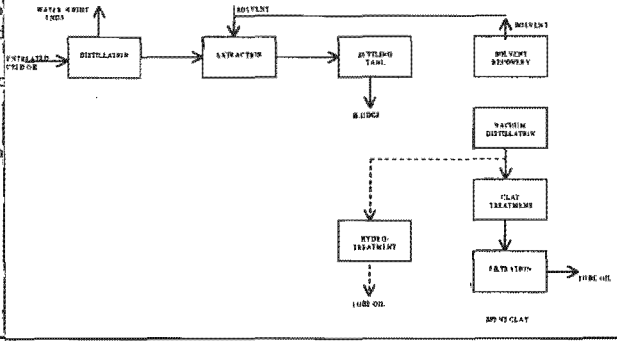


The BERC Re-refining Process

The BERC Re-refining Process was developed and patented b
mixed with a solvent system developed at BERC and composed

The solvent treatment stage is an integral step in the BERC tec
tower.

The resulting lube cuts are clay contacted or hydrotreated to im



The Interline Process

Interline technology employs liquid propane extraction for the

The process consists of the following steps

Extraction
Raw used oil is mixed with a propane-based solvent to extract t

Separation
The oil is separated from the propane and then flashed at atmos
with the solid residue deriving from the residue/water separatio

Interline started industrial operations with this process in 1993

2.7 METHODS EMPLOYED IN COMPARING USED OIL MANAGEMENT AND TECHNOLOGY OPTIONS

The purpose of the research presented in the thesis was to carry out a comparative assessment of the environmental performance of used oil recycling options. In this section of the report some assessment tools that have been used in the comparative assessment of used oil management options are reviewed and the findings of the assessments are presented.

2.7.1 Material and Energy Balances

Material and energy balances can be considered in-plant methods of comparing any two or more used oil management options. Based on a given quantity and quality of oil to be produced, the raw material, intermediate materials and energy consumption required for the production process are compared. The basis of comparison would be the quantities of materials consumed and possibly the volumes of wastes and emissions would also be considered. The related energy demands of the processes are also important in the comparisons. Available literature provides to some extent the overall mass and energy requirements for re-refining and reprocessing technologies. (McKeagan, 1992) However, the focus of these reports is not comparison but rather cost estimation and hence they lack the inventory detail that is required to make broader useful comparison of any two processes.

On the other hand there have been studies to compare used oil management options using material and energy balances. The focus of these studies has been to compare only the options of re-refining and burning. (Thompson and Brinkman, 1980)

Thompson and Brinkman (1980) presented a report giving a material and energy balance based comparison on burning and re-refining using the BERC Re-refining Process (also known as the BETC Process). For the comparisons to be possible a set of assumptions were given:

- Constant volume of reduced crude whether used oils burned or re-refined
- Reduced crude directly usable as fuel
- By-products assumed usable as fuel without further treatment
- Energy to remove water, fuel additives and sludge from the used oil included in the total energy consumption for the BERC Process
- Distillation bottoms from vacuum distillation useable for fuel without further treatment

The material paths followed by the used oil in the burning and re-refining options are shown in Figure 2.3 and Figure 2.4, and Table 2.12 providing summaries of the comparative energy balances.
(Thompson and Brinkman, 1980)

It should however, be noted that material and energy balances are very process specific and results obtained from comparisons are not relevant to the management options as a whole, but are specific to the technologies compared in the management options. For that reason it is difficult to obtain results that are comparable on wider scale and subsequently to make policy decisions other than those that relate strictly to the technologies and the processing plants compared.

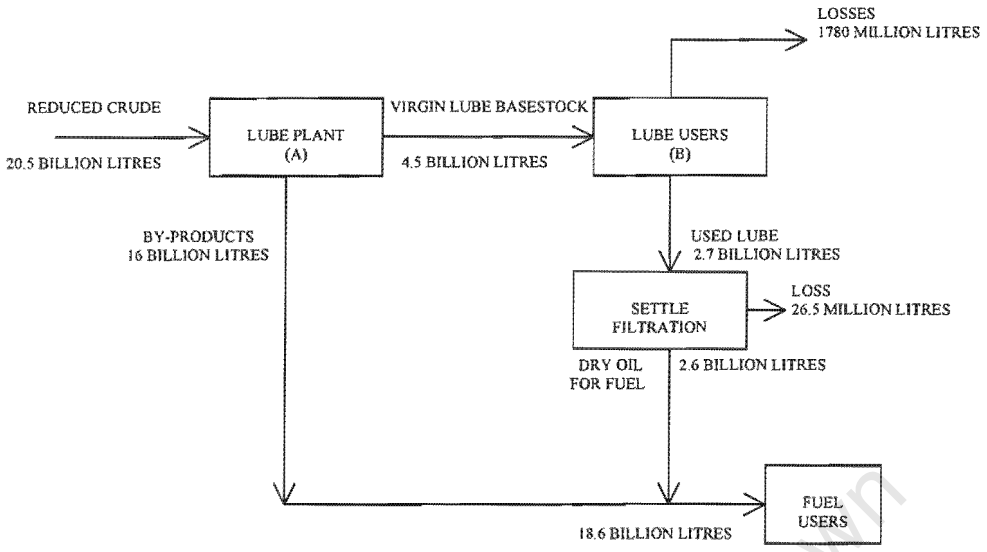


Figure 2.3 Material Balance on lube oil cycle for the Burning Option
Adopted from: Thompson and Brinkman, 1980
*1 GALLON = 3.785 LITRES

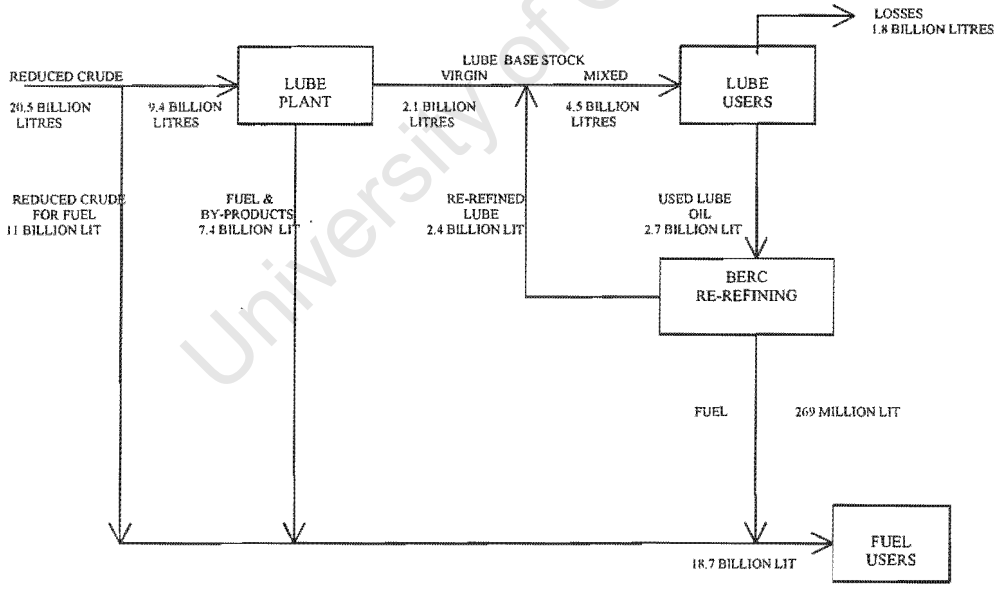


Figure 2.4 Material Balance on lube oil cycle for the Re-refining Option
Adopted from: Thompson and Brinkman, 1980
*1 GALLON = 3.785 LITRES

Table 2.12 Annual energy consumption and potential Savings

	Burning scenario	Re-refining scenario
Virgin lube production	34.5 x 10^{12} kJ	16 x 10^{12} kJ
Lube by BERC re-refining	--	4 x 10^{12} kJ
Fuels by settling & filtering	62.5 x 10^{6} kJ	--
Annual total energy consumption	**34.7 x 10^{12} kJ**	**19.8 x 10^{12} kJ**
Annual total energy advantage	--	14.8 x 10^{12} kJ

Adopted from: Thompson and Brinkman, 1980

2.7.2 Life Cycle Assessment to compare burning to re-refining

In CONCAWE Report (1996) the various used oil disposal options used in the European Union (EU) were ranked against a number of criteria such as environmental and health performance and economic viability. However the CONCAWE Report (1996) recommended that Life Cycle analyses be carried out produce overall ranking of the disposal options. Davies (2000) reports that several life cycle assessments have been published in the EU comparing re-refining to burning options for used oil management and these include:

- Coopers & Lybrand study for the EC, 1997
- French study conducted by Ecobilan and published by ADEME, 2000
- Italian study conducted by Ecobilan
- Industrial Institute of Norway study, 1995
- Ocopaul Institute study commissioned by the government of Lower Saxony in Germany
- German EPA study published in March 2000

Davies (2000) reports that the findings of these LCAs have been inconclusive over preferences for burning or re-refining of used oil.

During the course of the research literature was acquired for the Industrial Institute of Norway study and the French study conducted by Ecobilan and published by ADEME (2000). The structure and results of these studies will be summarised.

2.7.2.a A summary of the study by the Industrial Institute of Norway (1995)

This LCA study was commissioned by:

- Norwegian Ministry Of The Environment
- Norwegian Environmental Protection Agency

The screening LCA was carried out to compare the environmental and resource consumption impacts of the following product systems:

- One system for the production and use of lubricating oil, and the burning of waste oil. (the burning system)
- One system for the production and use of lubricating oil, and the re-refining of used lube oil (the re-refining system)

The LCA was based on inventory analysis of:

- Emissions
- Energy consumption

The reviewers of the LCA chose a functional unit (a basis for comparison) of 1000kg lubricating oil (lubrication + energy utilisation)

As in any tool used for comparison, the aim of the comparison (goal definition) and assumptions made must be clearly stated.
The goal definition of the LCA was:

- LCA to be carried out to compare environmental and resource impacts of existing system for the collection and burning of used lube oil to system for collection and re-refining used lube oil.

Some of the assumptions made were:

- Loss of energy supply from used lube oil burning plants must be replaced with fuel oil
- Losses of lubricating oil must be replaced by virgin oil

The aim of the project was to produce documentation and a relevant foundation for decision making about:

- the environmental impacts of the two systems
- the consumption of fossil fuel for the compared systems

- Provide recommendations for further research and analyses

The life paths of the used oils for the burning and re-refining options are shown in Figures 2.5 and 2.6. The report presents the results of the comparison in graphical form and Figure 2.7 gives a comparison of fossil fuels consumption over the life cycles of the two processes.

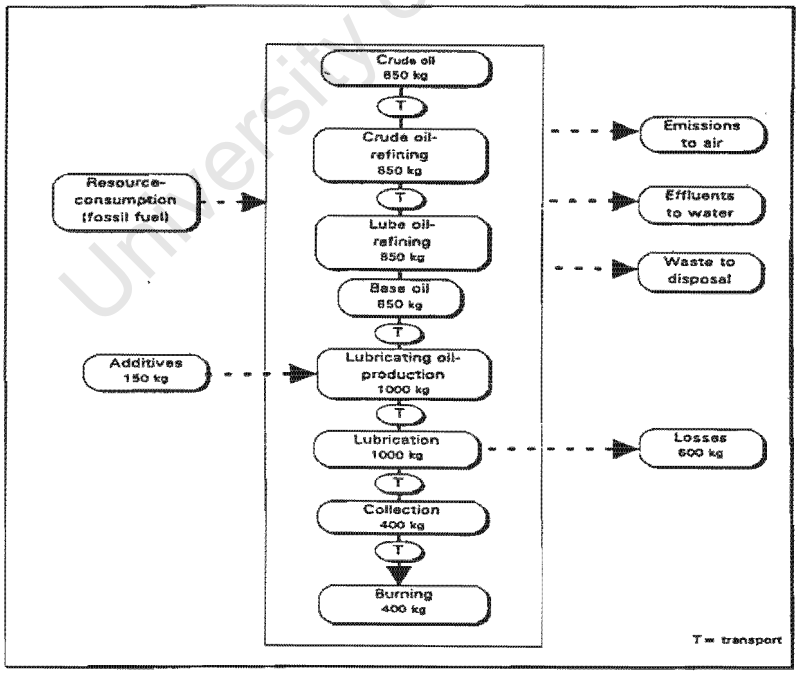


Figure 2.5 Product tree for the production, use, collection and burning of used lube oil (Source: Vold et al, 1995)

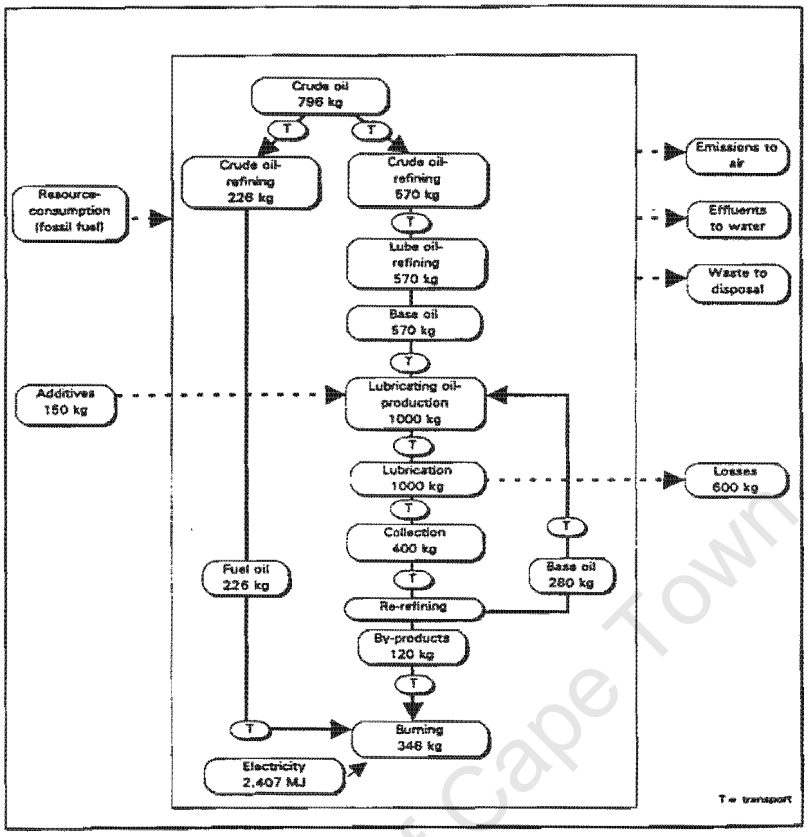


Figure 2.6 Product tree for the production, use and re-refining of used lube oil (Source: Vold et al, 1995)

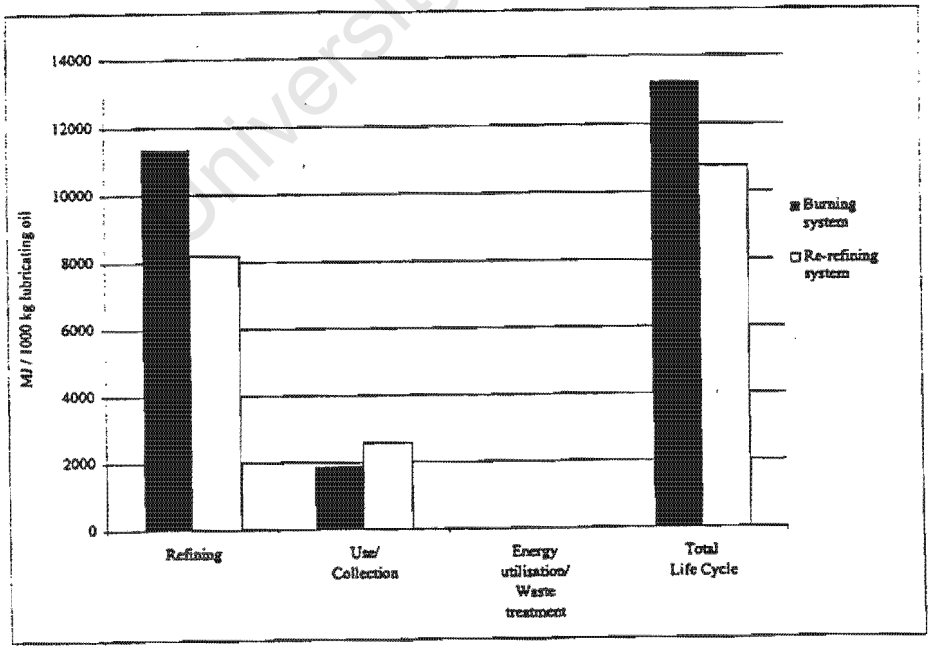


Figure 2.7 Consumption of fossil fuels in the phases and entire life cycles from 1000kg lube oil (Source: Vold et al, 1995)

The report concludes from the analysis of inventory data that re-refining is a better option for managing used lubricating oils when compared to burning.
(Vold et al, 1995)

2.7.2.b A summary of the French study conducted by Ecobilan and published by ADEME (ADEME, 2000)

An LCA study conducted by Ecobilan between 1997 and 1998 and published by a technical group commissioned by ADEME (Agency for Environment and Mastery of Energy) was carried out with the objective to review the strengths and weakness of the alternative used oil disposal options available in France.

In the study five different options disposing used oil of were compared, two being representative of the French scenario for used oil management at that juncture. The used oil disposal options representative of the French scenario were:

- Vacuum distillation followed by clay finishing
- Recovery for energy in cement kilns

The three remaining used oil recycling options considered in the study were, developed in other countries or studied in France in industrial pilot-scale. The three options that were analysed are:

- Hydrotreating
- Recovery for energy in asphalt coating plans
- Re-refining

The results of this study show that the different considered ways of disposing of used oil have globally a good impact on the environment. The following conclusions were made from the study:

- Emissions to water and waste generation are low in all considered options and they are not a major constituent for the environmental assessment.

- The major environmental concerns are related to air emissions and the impact related to, as well as the consumption of non-renewable energy.

- The best option for recycling used oil in France, from an energetic point of view is the substitution of fuels in cement kilns. The recovery as fuel in an asphalt coating plans has the same advantage, except for the atmospheric acidification and the possible toxicity of the emissions.

- Re-refining of used oil can be as effective as the recovery as fuel in cement kilns, except for the greenhouse effect, provided the re-refining operations that were in use in France were optimized. Several ways of optimization were indicated, in particular a better reclamation of the bottom of the column, the minimisation of the energetic need for the treatment and the use of fuel with a low rate of sulphur, chlorine and heavy metals. The use of new re-refining technologies was considered to be a potentially effective way of realizing the potential environmental gains from re-refining.

The results of the research conducted by Thompson and Brinkman (1980) using material and energy balances, and the LCA carried out by Vold et al (1995) as well as the French study published by ADEME (ADEME, 2000) indicate that re-refining is either better or equally good an option for managing used lubricating oils when compared to burning used oil. These results however have limited applicability to the South African environment but they assist in confirming that re-refining should also be considered as an option for managing used oil in the country.

2.8 CONCLUSIONS

The purpose of this chapter was to present the environmental and health concerns associated with used oil handling and to review the best available used oil management and technology options with special reference to their applicability to the South African environment. The literature survey shows that used oil management options can be broadly classified as controlled disposal options, options in which the used oil is burned to utilise its energy value and options in which the used oil is treated for re-use and recycling. In each of these broad categories numerous technology options have been presented and discussed.

Even though the literature study indicates that there are many different used oil management and technology options that may be considered for managing used lubricating oils collected in South Africa, based on the technology, environmental performance and data availability considerations the following used oil management options were selected for purposes of building a life cycle analysis model to be used in the comparative environmental analysis of used oil management scenarios in South Africa:

- Re-refining of used lubricating oil using the Revivoil Re-refining process
- Reprocessing for subsequent burning using the Revivoil Reprocessing configuration-with two burning destinations: industrial furnaces and brick kilns
- Burning untreated used oil in a cement kiln
- Burning untreated oil in an industrial furnace

The findings from broad based comparative studies on the environmental performance of re-refining and burning options for used oil have also been reviewed in this chapter. The results of studies carried out by Thompson and Brinkman (1980) using a mass and energy balance analysis, as well as LCA based studies carried out by Vold et al (1995) and the French study published by ADEME (ADEME, 2000) were presented and discussed. These studies show that the comparisons of the environmental performance between re-refining and burning options may be verified from broad based studies and suggest that the use of LCA in the comparative assessment of the environmental performance of management scenarios for used oils collected in South Africa will reveal differences between options and thus opportunities for improvement.

In this chapter LCA has been mentioned as a tool for environmental analysis and some of the results of the work done by Vold et al (1995) as well as the French study published by ADEME (ADEME, 2000) have been presented, albeit without a prior presentation of its working procedure. LCA methodology and procedure are presented in Chapter 3 of the thesis.

Chapter 3

Life Cycle Assessment Methodology and Procedure

3.1 INTRODUCTION

The purpose of this chapter is to present Life Cycle Assessment (LCA) as a tool for environmental assessment. LCA is defined by SETAC (1993) as:

"a process to evaluate the environmental burdens associated with a process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses to the environment; and to identify and evaluate opportunities for improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal".

In this chapter methodology and procedure that is followed in carrying out an LCA project is briefly described and the applicability of LCA for environmental management is reviewed. It should be noted that several good books (Ciambrone, 1993; Vigon et al, 1994; Graedel, 1998; Hauschild and Wenzel, 1998; Wenzel et al, 1997) have been written on the subject and that international norms have been formulated. It is thus not the purpose of this chapter to give an exhaustive account.

The chapter begins by setting the background for LCA use by looking at LCA historical development and the main factors, which brought about its recognition and increased application. The formal procedure for carrying out an LCA is then discussed and each of the sub-stages of LCA methodology are individually described. After the formal procedure for carrying out an LCA project has been presented, the strengths and weaknesses of LCA as a tool for environmental assessment are reviewed.

The chapter is concluded by giving an outlook on the various stages of LCA that are applied to the assessment of used lubricating oil management in the remaining chapters of the thesis.

3.2 A HISTORICAL OVERVIEW OF LCA

Vigon et al (1994) report that LCA had its beginnings in the 1960s when emerging concerns over the limitations of raw materials and energy sparked interest in finding ways to accumulatively account for energy use and to project future energy use. One of the first publications on the subject was a presentation at the World Energy Conference in 1963 by Harold Smith, who reported on his calculation of cumulative energy required for the production of chemical intermediates. Later in the 1960s global modelling studies were published in "The Limits to Growth" (Meadows et al, 1972) and "A Blueprint for Survival' (Club of Rome). These studies involved the demand for finite raw material and energy resources, resulting in predictions of rapid depletion of fossil fuel and climatological changes resulting from waste heat if unrestrained consumption of finite raw material and energy resources by an increasing world population continued. These studies stimulated more detailed calculations. During this period about a dozen studies were performed to estimate costs and environmental implications of alternative sources of energy.

In 1969 researchers initiated a study for the Coca Cola company that laid the foundation for the current methods of Life Cycle analysis, in a comparison of the different beverage containers to determine which container had the lowest releases to the environment and least affected the supply of natural resources. (Vigon et al, 1994) In the early 1970s other companies in the USA and Europe performed similar Life Cycle analyses. The process of quantifying the use of resources and the release of products into the environment became known as Resource and Environmental Profile Analysis (REPA) in the USA. In Europe it was called Ecobalance.

During the 1970s and early 1980s interest in REPA waned in the USA. However, interest in the process increased in Europe. The Green Movement, especially the formation of green political parties in Europe reawakened interest in the subject. When solid waste became an issue world wide in the late 1980s, the Life Cycle analysis technique re-emerged as a tool for analysing environmental problems. (Ciambrone, 1997). Over the past 20 years most Life Cycle Inventories have examined different forms of product packaging such as beverage containers, food containers, fast food packaging and shipping containers. As of 1992, approximately 50% of the 90 or so LCAs which had been performed dealt with packaging, 10% were on products from the chemicals and plastics industry, and a similar quantity dealt with building materials and energy production (Christiansen, 1993).

The overall LCA framework continues to evolve and there are aspects of the life-cycle process which are still under review by various institutions. Initial LCA work lacked a theoretical framework and seemingly similar studies often yielded conflicting results. In the 1990s the Society of Environmental Toxicology and Chemistry (SETAC), as a scientific and professional society provided infrastructure, credibility, resources and expertise for the development of a technical framework for the conduct of Life Cycle Assessment. (Vigon et al, 1994)

The international Standards Organisation (ISO) has recently developed a series of environmental standards dealing with LCA under the ISO 14000 environmental management series. Four major subject areas in Life Cycle analysis considered included policies and practise, general principles, life-cycle inventories and methods of impact and improvement assessment. ISO 14040 gives the principles and framework of LCA (SABS ISO 14040, 1997). ISO 14041 is the code for Goal and Scope definition and inventory analysis (SABS ISO 14041,1998), ISO 14042 relates to Life Cycle Impact Assessment (LCIA) and ISO 14043 covers Life-cycle Interpretation. (Kuhre, 1995; SABS ISO 14041, 1998; Ryding, 1999; Lecouls, 1999) The work to standardise environmental management methods has been carried out with the aim of creating a world-wide environmental accreditation and certification system which is expected to ultimately result in the reduced release of hazardous wastes into the environment (Kuhre, 1995).

3.3 THE PROCEDURAL FRAMEWORK FOR CARRYING OUT AN LCA

The Society for Environmental Toxicology and Chemistry (SETAC) has taken an active role in the development of the science and practice of LCA. In addition the International Standards Organisation (ISO) has developed standards to harmonise the practice of LCA.

ISO and SETAC specify the main components in the LCA process as *goal definition and scoping, inventory analysis, impact analysis and interpretation.*

- The ***goal definition*** component of an LCA shall unambiguously state the reason for carrying out the LCA, the intended use of the results, the intended audience for the result, initial data quality goals, and the type of critical review process to be employed. The scope of the study includes the system definition, the system boundaries, data requirements, assumptions and limitations. (SABS ISO 14041, 1998; Consoli, 1995)

- The ***inventory analysis*** component is a technical, data-based process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes,

and other releases for the entire life-cycle of a product, process or activity. (Vigon et al, 1994; SABS ISO 14040, 1997)

- The ***impact analysis*** component is a technical quantitative, and/or qualitative process to characterise and assess the effects of the resource requirements and environmental burdens (atmospheric and waterborne emissions, and solid wastes) identified in the inventory stage. The analysis should address both ecological and human health impacts, resource depletion and possibly social welfare. (Vigon et al, 1994) Whilst agreement has been reached on the methodological framework for impact analysis (ISO 14042, 1999), scientific methods are currently subject of intense debate. (Owens, 1999) There still exists scope in life cycle impact analysis to verify a mix of subjective judgements and technical issues which result from a wide range of disparities in spatial and temporal scales as well as mechanistic considerations between life cycle impact analysis and a number of environmental processes. (SABS ISO 14040, 1997; Owens, 1999; Ryding, 1999)

- The ***interpretation*** component of LCA is a systematic evaluation of the needs and opportunities to reduce the environmental burdens associated with energy and raw material use and waste emissions throughout the life-cycle of the product, process or activity. This analysis may include both qualitative and quantitative measures of improvements. (Vigon et al, 1994) According to ISO 14040 interpretation may take the form of conclusions and recommendations to decision makers, consistent with the goal and scope of the study (SABS ISO 14040, 1997; Lecouls, 1999)

Practise has brought about the recognition that LCA is an iterative technique, and as data and information are collected, various aspects of the scope may require modification in order to meet the original goal of the study. This iterative process carries through all the stages of LCA as modifications and revisions become necessary due to unforeseen limitations, constraints or as a result of additional information. (SABS ISO 14041, 1998; Graedel, 1998) The stages of LCA and their iterative nature are presented in diagrammatic form in Figure 3.1. These stages will be described in sections 3.3.1 to 3.3.5 of the chapter.

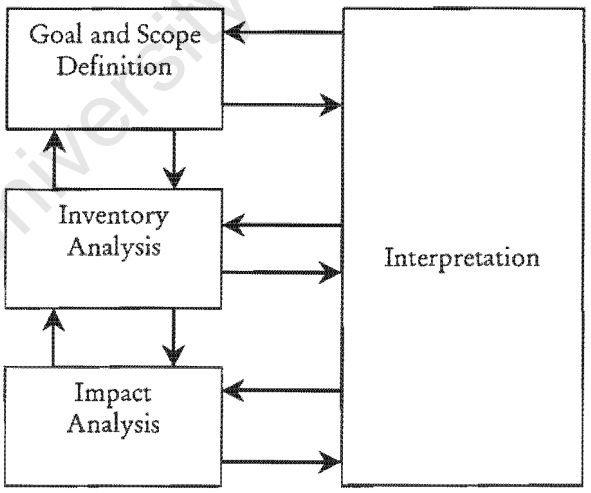


Figure 3.1 Stages in the Life Cycle Assessment of a technological activity. (The arrows indicate the basic flow of information) (Graedel, 1998)

3.3.1 Goal Definition and Scope

An LCA process begins with a conceptual goal definition phase to define both the purpose of performing the LCA and the scope of the analysis. In the goal and scope definition stage of performing the LCA the following factors have to be defined:

3.3.1.a The purpose of the LCA

In defining the goal and scope of the LCA the following components at a minimum should be defined:

- How will the results be used,
- The product, process or activity to be studied,
- Reasons for conducting the study,
- The elements not to be addressed,
- The elements of the analysis.

At the onset of the study the level of specificity must be decided. The objectives of an LCA can be met by one of the following approaches

- Full scale life cycle
- Partial or comparative life-cycle
- Individual stages or processes

The partial or comparative life cycle approach is much like the full-scale life-cycle, but allows for stages to be omitted if they have been studied before or are static for the purposes of the study. An LCA can be limited to individual stages or processes if a new process is being considered or if the product finds use in another application or market. (Curran, 1993)

3.3.1.b The choice of functional unit and reference flow

The International Standards Organisation (ISO) document (SABS ISO 14041, 1998) on Life Cycle Assessment states that, in defining the scope of the LCA study, a clear statement on the specification of the functions (performance characteristics) of the system shall be made.

The functional unit defines the quantification of these identified functions. The functional unit shall be consistent with the goal and scope of the study. One of the primary purposes of the functional unit is to provide a reference to which the input and output data are normalised (in the mathematical sense). Therefore the functional unit has to be clearly defined and measurable.

Having defined the functional unit, the amount of product which is necessary to fulfill the function shall be quantified and the result of this quantification is the reference flow.

3.3.1.c Initial system boundaries

Once the goal and scope for preparing a life-cycle inventory have been determined, the system should be defined. A system is a collection of operations that together perform the clearly defined function. In defining the system to be analysed, system boundaries should be defined, which in turn define the unit processes to be included in the system to be modelled. Decisions will have to be made on the level of detail to which these unit processes shall be studied. Decisions shall also be made regarding which releases to the environment shall be evaluated and the level of detail of this evaluation. The criteria used to assist in the choice of inputs and outputs should be clearly understood and described, and any decisions to omit life-cycle stages, processes or inputs/outputs shall be clearly stated and justified. (SABS ISO 14041, 1998; Curran, 1993; Vigon et al, 1994)

3.3.1.d Description of data categories and data quality requirements as well as criteria for data inclusion and exclusion (SABS ISO 14041, 1998)

According to ISO 14041 (SABS ISO 14041, 1998) the data required for the LCA study are dependent on the goal of the study. Such data may be collected from the production sites associated with the unit processes within the system boundaries, or may be obtained or calculated from published sources.

Descriptions of data quality are important to understand the reliability of the study results and properly interpret the outcome of the study. Data quality requirements shall be specified to enable the goal and scope of the study to be met. Data quality should be characterised by both quantitative and qualitative aspects as well as by the methods used to collect and integrate those data.

Data quality requirements should be included for the following parameters

- time-related coverage: the desired age of the data (e.g. within the last five years) and the minimum length of time (e.g. one year) over which data should be collected
- geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study (e.g. local, regional, continental, global)
- technology coverage: technology mix (e.g. weighted average of the the actual process mix, best available technology or worst operating unit)

Further descriptors which define the nature of the data, such as that collected from specific sites versus data from published sources, and whether data should be measured, calculated or estimated, should be considered.

Other aspects of data quality that may be considered are precision, completeness, representativeness, consistency and reproducibility.

It is often not practical or possible to include all data in an LCA and criteria for including or excluding data or data sets have to be formulated. The criteria for including or excluding data may be based on mass or energy contributions to the life cycle as well as potential environmental impacts. The criteria and the assumptions on which they are established should be clearly stated. (SABS ISO 14041, 1998)

3.3.2 Inventory Analysis

The initial planning of an LCA carried out during the goal and scope definition is proceeded by the life cycle inventory analysis which is concerned with data collection and calculation procedures. (SABS ISO 14041, 1998)

A complete life-cycle inventory includes and quantifies the resource and energy use and environmental releases throughout the product life cycle as illustrated in Figure 3.2 (Curran, 1993; Vigon et al, 1994). The illustrated stages of Life Cycle Inventory (LCI) analysis are described below.

Raw material acquisition: the boundaries of this element include all activities needed for the acquisition of all raw materials and ends with the first manufacturing or processing stage that refines the raw materials.

The **manufacturing** stage encompasses three steps;

- Materials manufacture which are the activities required to process raw material into a form that can be used to fabricate a particular product or package. Normally the production of many intermediate chemicals or materials is included in this category. The transport of intermediate materials is also included

- Product fabrication covers the process steps that use the raw or manufactured materials to fabricate a product ready to be filled or packaged. This step often involves a consumer product that will be distributed for retail sales, but the product could also be distributed for use by other industries.

- Filling/packaging/distribution are processes that prepare the final products for shipment and that transport the products to retail outlets (Vigon et al 1994)

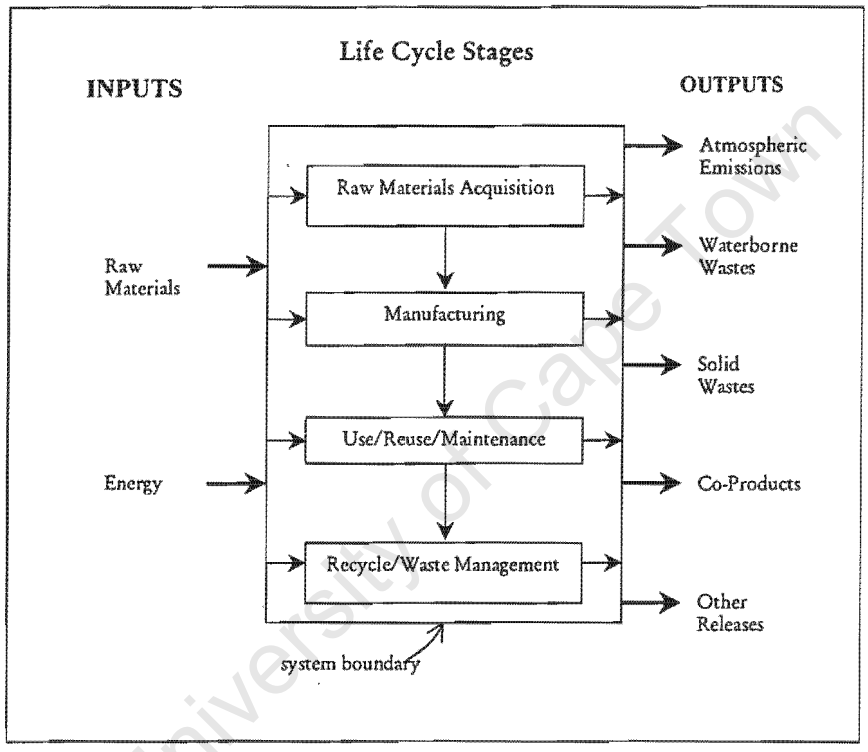


Figure 3.2 Defining the system boundaries and activities in Life Cycle Inventory Analysis. (adopted from Vigon et al, 1994)

The **Use/Reuse/Maintenance** Stage begins after the distribution of products or materials for the intended use and includes any activity in which the product or package may be reconditioned, maintained, or serviced to extend its useful life. (Vigon et al, 1994)

Recycle, Waste Management: The recycle step involves reclaiming materials out of the waste management system and returning them into the manufacturing or processing stage. Waste management is the effective disposal of any material released to any environment at all stages of life cycle. Waste management includes any mechanisms for treating, handling, or transportation of wastes prior to their release to the environment. (Curran, 1993)

The operational steps for LCI are outlined in sections 3.3.2.a to 3.3.2.e of this chapter.

3.3.2.a Preparation for data collection

The system boundaries defined for an LCA in goal definition and scope phase will normally consist of a series of interrelated unit processes and their associated data categories. The process of collecting data may span several reporting locations and published literature, and a systematic method of data collection is required to ensure uniform and consistent understanding of the systems being modelled. (SABS ISO 14041, 1998)

ISO 14041 therefore advises a systematic method of data collection that includes drawing of specific process flow diagrams that outline all unit processes to be modelled and their interrelationships. In addition to this each unit process should be described in detail and the data categories associated with each unit process should be listed. Other factors that should be considered concern data collection and data calculation techniques as well as making provision for reporting on special data categories and irregularities associated with the data provided. (SABS ISO 14041, 1998)

Vigon et al (1994) proposed the use of an inventory checklist while preparing for data collection and during the actual data collection process. The inventory checklist is a tool that is used to guide data collection and validation, and to enable the construction of a computational model within defined inventory boundaries. The following decision areas should be addressed in the checklist

- Purpose of inventory
- System boundaries
- Geographic scope
- Types of data used
- Data collection and synthesis procedures
- Data quality measures
- Computational model construction
- Presentation of the results

The analyst performing the LCA can use the checklist to help ensure that all important stages and categories of information are included. The checklist can also help clarify the issues, boundaries and conditions to be dealt with in a particular study. The checklist is also used by the analyst to collect and qualify data from facilities.
(Vigon et al, 1994)

3.3.2.b Data gathering

For data gathering purposes the life-cycle inventory may be appropriately viewed as a series of subsystems. A "subsystem" is defined as an individual step or processes that is part of the defined production system.

Each subsystem requires inputs of materials and energy, transportation of product produced; and has outputs of products and co-products, atmospheric emissions, waterborne emissions and solid wastes. For each subsystem the inventory analyst should describe materials and energy sources used and the types of environmental releases. Actual activities that also occur should be described.

Data collected for an inventory should always be associated with a quality measure, and a description of how data were collected is useful in judging quality.
(Vigon et al, 1994)

The procedures used for data collection will be expected to vary with each unit process in the LCA model at a given location. Procedures may vary due to the composition and qualification of

the participants of the study for a unit process. There may also be a need to satisfy both proprietary and confidentiality requirements and such reasons for procedural variation in the data collection process should be documented. (SAB ISO 14041, 1998)

3.3.2.c Calculation procedures

Following data collection, calculation procedures are needed to generate the results of the inventory of the defined system for each unit process and for the defined functional unit of the product system that is to be modelled (SABS ISO, 1998).

The data calculation process begins with the validation of data. Validation may involve the verification of data using mass balances, energy balances and/or comparative analysis of emission factors. The validation of data shall be followed by a process of relating data to unit processes wherein for each unit process, an appropriate reference flow shall be determined (e.g. 1kg of material). The quantitative input and output data of the unit process shall be calculated in relation to this reference flow.
After relating data to unit processes, data is related to a functional unit for the aggregated system of consisting of the interconnected unit processes to allow for calculations on the complete system. This is accomplished by normalising the flows of all the unit processes to the functional unit and the calculation should result in all system input and output data being referenced to the functional unit.

An important factor to be considered for a process making a system with co-products is to determine the energy and material requirements, and environmental releases to be attributed to the production of each of the co-products using a technique called co-product allocation. Co-product allocation methods may be based on co-product relative weight and/or potential environmental impacts. (Vigon et al, 1994; SABS ISO 14041, 1998)

3.3.2.d Construction of a computational model

The construction of a computational model is a step that is not explicitly defined in the ISO 14041 standard for LCA goal definition and scope and inventory analysis. (SABS ISO 14041, 1998) However, the data calculation process in inventory analysis is most easily accomplished through the construction of a computational model, which can be created using a computer spreadsheet or specialised accounting techniques provided by life-cycle analysis software. The system accounting data that result from the computational model give the total results for the energy and resource use and environmental releases from the overall system.

It is important that each subsystem be incorporated into the model with its related components and that each be linked together in such a way that inadvertent omissions and double counting do not occur. The computational model is also used to perform sensitivity analysis calculations on the model by temporarily modifying one or more parameters and changing results. (Vigon et al, 1994)

3.3.2.e Presentation of results

The analyst needs to select a format for presenting results with a content and format that is consistent with the purpose of the study. When writing the report it is important to thoroughly describe the methodology used in the analysis. The report should explicitly define the systems analysed and the boundaries that were set. The basis for comparison among systems should be given, and any equivalent usage ratios that were used should be explained.

The life-cycle analyst must develop a format for the presentation that increases comprehension of results without oversimplifying them. (Vigon et al, 1994)

3.3.3 Life Cycle Impact Analysis (LCIA) and Evaluation

The purpose of Life Cycle Impact Analysis (LCIA) is to assess a system's life-cycle inventory results with the aim of understanding their potential environmental significance. LCIA uses impact categories and associated indicators to present LCI results with regard to one or more environmental issues. Figure 3.3 shows the framework for LCIA as laid down in the now adopted ISO 14042 standard on LCIA (Boustead Consulting, 1998).

The most recent discussions within SETAC and ISO have led to significant changes in the description of LCIA. Both SETAC and ISO now describe the LCIA outcome as LCIA indicators rather than as, 'a technical, quantitative and/or qualitative process to characterise and assess the effects of environmental burdens identified in the inventory component' -an initial description given for impact assessment in LCA. This change in LCA understanding and thinking has been brought about by the recognition that the development of a general consensus in LCIA cannot provide a characterisation of assessment of environmental effects. Secondly, it was recognised that a more detailed understanding of the wide variation in technical abilities and environmental relationships of a number of LCIA indicators as well as the scoring nature of some indicators is still needed. (Owens, 1999)

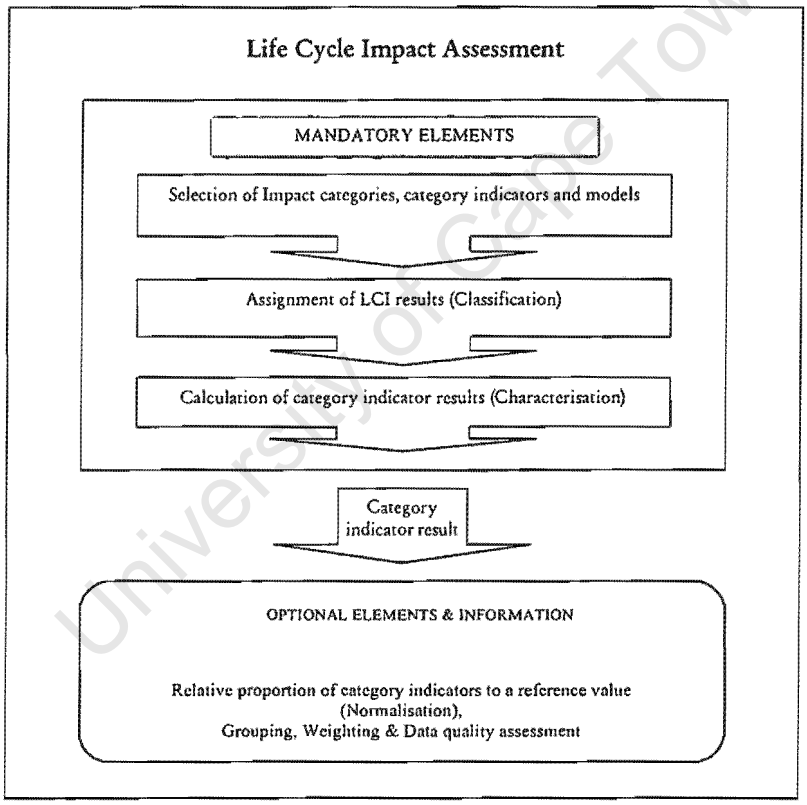


Figure 3.3 Elements of LCIA as laid out in ISO 14042 (Boustead Consulting, 1998)

As shown in Figure 3.3, the first step in LCIA is the identification of stressors and the environmental concerns to which they are related. Stressors are items identified in the inventory analysis that have the potential to introduce changes in environmental properties. These potential impacts do not take into account the actual sensitivity of the receptor, and cannot therefore be verified by measurement.

The more challenging approach is to predict actual impacts, which in principle, can be verified by measurement. An example is the Impact Pathway Analysis (IPA) (Krewitt et al, 1998) developed

within the European Union (EU) to support the quantification and valuation of environmental impacts resulting from electricity generation technologies. To understand the association between environmental burdens and resulting impacts, the impact pathway analysis attempts to describe the chain of casual relationships from the emission of a burden through to transport and chemical conversion in the environment to the impact on various receptors such as humans, crops, building materials or ecosystems. IPA finds use in site-specific assessments to be able to predict actual impacts for which voluminous quantities of information have to be verified. IPA's application is still limited to airborne pollutants as current scientific understanding of biochemical and biophysical mechanisms is still too limited to enable the actual impact assessment of other forms of environmental pollution. (Krewitt et al, 1998)

The other mandatory as well as optional elements of LCIA as indicated in Figure 3.3 are described in greater detail in section 3.3.3.a to 3.3.3.c of the chapter.

3.3.3.a Classification and Characterisation

Classification begins with raw data from the inventory on flows of materials and labelling this data according to the environmental effect categories they contribute to. For example, emissions from an industrial process using a petroleum feedstock may be known to include methane, butane and formaldehyde. Classification assigns the first primarily to global warming, the second to smog formation and the third to human toxicity. (Graedel, 1998) In this example global warming and human toxicity are environmental effect categories or impact categories to which the respective emissions contribute. The second working group on LCIA of SETAC-Europe (WIA-2) presented a proposed list of impact categories for LCIA, with the main distinction being input related and output related categories. (Udo de Haes et al, 1999) The proposed impact categories are presented in Table 3.1

Table 3.1 Proposed impact categories for LCIA (Udo de Haes et al, 1999)

Input related categories	Output related categories
Extraction of abiotic resources	Climate change
Extraction of biotic resources	Stratospheric ozone depletion
Land use-	Human toxicity
-subcategory: increase of land competition	Eco-toxicity
-subcategory: degradation of life support functions	Photo-oxidant formation
-subcategory: biodiversity degradation	Acidification
	Nutrification/Eutrophication

Some impact categories in LCIA are explained in greater detail below and their characterisation is discussed. Characterisation, as illustrated in Figure 3.3 is a step in LCIA in which different stressor-impact relationships are combined into a common framework. An example is the use of ozone depletion potentials, in which the effects of a molecule of one substance on stratospheric ozone are compared quantitatively with those of another. (Graedel, 1998)

The impact categories that are presented below are described in the characterisation process which is presented by Hauschild and Wenzel (1998) and was developed over a four year period under the Danish EDIP (Environmental Design of Industrial Products) programme. The EDIP programme was conducted by a team representing the Technical University of Denmark, five Danish companies, the Confederation of Danish Industries and the Danish Environmental Protection Agency.

- **Global Warming** (Hauschild and Wenzel, 1998)

  Most of the radiant energy which the atmosphere and the earth receive from the sun in the form of short-wave radiation (UV and visible light) is reflected directly or re-emitted from the atmosphere or the surface of the earth as longer wave infrared (IR) radiation.

  Part of the IR radiation emitted is absorbed by gases, aerosols and particles in the earth's atmosphere, thereby increasing the temperature of the atmosphere. This "natural" greenhouse effect is predominantly due to the presence of water vapour, which is thus the most important greenhouse gas, in the lower 10-15km of the atmosphere (troposphere). It is estimated that as a consequence of this natural greenhouse effect, the atmospheric temperature at the earth's surface is about 33° higher than it would otherwise be.

  The focus in environmental assessment is on the "man-made greenhouse effect", which is an increase in atmospheric temperature over and above the natural greenhouse effect, caused by man-made emissions of substances or particles which can influence the earth's radiation balance. The most important emissions resulting from human activities which can enhance the greenhouse effect are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons (hydrocarbons containing chlorine, fluorine and bromine). Ozone (O_3) is also a greenhouse gas, but the extent of its contribution is currently uncertain.

  Relative to the natural greenhouse effect, the man-made contribution is modest. The average global temperature is believed to have risen between half and one degree in the last 100 years as a consequence of industrial emissions. Of particular concern is the speed with which the increasing emission of greenhouse gases is changing the radiation balance of the atmosphere. However, the modelling of climatic consequences continues to be encumbered with a high degree of uncertainty because of the complexity of the models and the difficulties in calibrating and verifying them.

  The Inter-governmental Panel on Climate Change (IPCC) has developed an equivalency factor system which can weight various substances according to their potencies as greenhouse gases. The system allocates the various substances a global warming potential (GWP), which is calculated as the anticipated contribution to warming from an emission over a chosen time period from a given emission of the substance divided by the contribution to warming from an emission of a corresponding quantity of CO_2. Multiplying a known emission of a greenhouse gas by the relevant GWP yields the magnitude of the CO_2 emission, which under the chosen conditions, will result in the same contribution to global warming, i.e. the emission of the greenhouse gas expressed in CO_2-equivalents.

  CO_2 was chosen by the IPCC as the reference substance because it is the substance which makes by far the largest contribution to the greenhouse effect (Hauschild and Wenzel, 1998).

- **Stratospheric ozone depletion** (Hauschild and Wenzel, 1998)

  The earth's atmosphere receives ultraviolet radiation from the sun. The UV radiation is so strong that it would render life on earth as we know it today impossible if it reached the earth at full intensity. Ozone molecules in the stratosphere absorb large quantities of this UV radiation, thus removing life-threatening UV-C radiation entirely and reducing the intensity of harmful UV-B radiation.

  The concentration of ozone is significantly higher in the stratosphere than in other parts of the atmosphere. The stratosphere is an atmospheric layer above the troposphere which follows from about 15-50 km from the earth's surface. The increased occurrence of ozone is attributed to the formation of ozone from oxygen under the influence of energetic UV radiation in the stratosphere and from the relatively high stability of ozone in the bottom stratum of the stratosphere.

The quantity of ozone present in the undisturbed stratosphere is the result of an equilibrium among a large number of natural processes of formation and degradation. A number of substances which occur naturally in the stratosphere are involved in the breakdown of ozone: methane (CH_4), nitrous oxide (N_2O), water vapour (H_2O) and chlorine and bromine compounds such as methyl chloride (CH_3Cl) and methyl bromide (CH_3Br) are among the most important. The breakdown of ozone occurs via chemical reactions.

Human activities have caused an increase in the quantity of substances in the stratosphere which contribute to the chemical breakdown of ozone, especially over the last 40 years. The reason is emissions of a large number of chlorine and bromine containing hydrocarbons, especially CFCs, tetrachloromethane, 1,1,1-trichloroethane, HCFCs, halons and methyl bromide. A common feature of all these substances is that they are so chemically stable in the lower parts of the atmosphere that they survive long enough (several years) to reach the stratosphere, where they can release their content of chlorine or bromine under the influence of UV radiation.

The calculation of the potential contribution to ozone depletion requires a set of factors which express the magnitude of the potential contribution to ozone depletion for all substances in question. An example of a system that is used in the calculation of potential contributions to ozone depletion is the total or time dependent Ozone Depletion Potential (ODP). A substance's ODP is calculated as the expected contribution to stratospheric ozone depletion at steady state from a given emission relative to monofluorotrichloromethane, $CFCl_3$, designated 'CFC11'. CFC11 was chosen as a reference substance because it has been well studied and has been one of the most important ozone depleting substances.

For an ozone depleting substance (a), the effects of emission of a given mass relative to emission of the same mass of CFC11 are considered. The substance's ODP value is given as:

$$\text{ODP} = \frac{\text{calculated global } O_3 \text{ depletion caused by substance(a)}}{\text{calculated global } O_3 \text{ depletion caused by CFC11}}$$

- **Photochemical ozone formation** (Hauschild and Wenzel, 1998; Forbes, 1999)

Photochemical ozone formation proceeds through the following four steps:

- Reaction between volatile organic compounds (VOCs) or carbon monoxide (CO) and OH to form peroxy radicals
- Peroxy radicals oxidise NO to NO_2
- NO_2 is split by sunlight with the formation of NO and release of oxygen atoms
- Oxygen atoms react with molecular oxygen, O_2, to form ozone

Increased concentrations of reactive substances, photo-oxidants, which are injurious to the health of living organisms, can rise via the photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the troposphere.

The photo-oxidants include a large number of different unstable oxidizing substances formed when volatile organic compounds react with various oxygen compounds and oxides of nitrogen, NO_x, which are naturally present in the troposphere. The most important of the oxygen compounds are hydroxyl radicals (OH). The most important individual substances among the photo-oxidants are ozone (O_3), and peroxyacetyl nitrate, PAN. But intermediate products from the oxidation of VOCs also contribute to the injurious effects. It is thus not VOCs per se which cause the environmental problems associated with photochemical ozone formation, but the products of their conversion.

The capacity to contribute to photochemical ozone formation in the troposphere can vary greatly for different organic substances. The potential contribution to photochemical ozone formation from a substance is described by its Maximum Incremental Reactivity (MIR) in American literature or its Photochemical Ozone Creation Potential (POCP) The reference substance is ethylene, C_2H_4 and the equivalent POCP of a substance (a) is calculated as:

$$POCP = \frac{\left(\frac{\text{change in photo-oxidant creation on change in emission of gas(a)}}{\text{total emission of gas(a)}}\right)}{\left(\frac{\text{change in photo-oxidant creation on change in emission of ethylene}}{\text{total emission of ethylene}}\right)}$$

- **Acidification** (Hauschild and Wenzel, 1998)

Acidification of soil or aquatic ecosystems can be defined as an impact which leads to a fall in the system's acid neutralising capacity, (De Vries and Breeuwsma, 1987), that is a reduction in the quantity of substances in the ecosystem which are able to neutralise hydrogen ions which may be added to the system. A number of acidifying substances (NO_x, SO_2, HCl, HF and NH_3) may be emitted to the air by industrial processes.

Metals, surface coatings and mineral building materials exposed to wind and weather are currently being degraded due to the acidification effect at a rate which is unparalleled in historic terms, with consequent major economic costs and loss of irreplaceable historic monuments everywhere in the industrialised world (Hauschild and Wenzel, 1998).

Other environmental problems associated with acidification include leaching of nutrients from soils and fish mortalities in acidified waters. Acidification classification factors are derived from the propensity of a substance to release protons, as compared to SO_2. (Forbes, 1999)

- **Nutrient enrichment (Eutrophication)** (Hauschild and Wenzel, 1998)

Eutrophication can be defined as an enrichment of the aquatic environment with nutrient salts which leads to an increase in the production of planktonic algae and higher aquatic plants, which in turn leads to a reduction in the quality of the water and a reduction in the value of the exploitation which occurs in the area. (Christiansen et al, 1993) The algae sink to the bottom and are broken down with consumption of oxygen in the bottom layer. As the oxygen concentration approaches zero, poisonous substances such as hydrogen sulphide (H_2S) are formed in the sediments, where they accumulate in gas pockets which, on their release, kill those organisms exposed to them.

The formula for the average composition for an aquatic organism is $C_{106}H_{263}O_{110}N_{16}P$ (Stumm and Morgan, 1981). The availability of the elements Carbon, C, Hydrogen, H, and oxygen, O, and of trace elements is rarely a limiting factor in the growth of primary producers in aquatic environments. In practice one of the two last macronutrients, nitrogen, N, and phosphorous, P, is therefore almost always the limiting element for the growth of primary producers, and it is therefore reasonable to regard only the element nitrogen and phosphorous as contributors to nutrient enrichment.

Substances which contain nitrogen or phosphorous in a biologically available form are therefore classified as potential contributors to nutrient enrichment. The most significant sources of nutrient enrichment are the agricultural use of fertilizers and the emission of oxides of nitrogen from energy production's incineration processes, and the contents of N and especially P from wastewater from households and industry.

In the calculation of nutrient enrichment potentials for emissions from the processes in a product system, the magnitude of the emissions must be expressed in the form of their contributions to nitrogen and phosphorous to the environment. In the calculation of nutrient enrichment potentials for substances the potentials of the emissions must be expressed in the form of their contribution of nitrogen or phosphorous to the environment. In situations where it is desirable to reduce the complexity of the results of the environmental assessment by expressing the nutrient enrichment as one equivalent, so that the contributions of nitrogen and phosphorous are aggregated, the impact potential is expressed as an equivalent emission of NO_3^-.

- **Ecotoxicity** (Hauschild and Wenzel, 1998)

A substance is classified as ecotoxic if it is toxic to organisms in a manner which affects the functioning and structure of the ecosystems in which the organisms live. Apart from the substance's toxicity, such properties such as persistence (low degradability in the environment) and the ability to bio-accumulate are considerations which are included in the classification of a substance's ecotoxicity. When dealing with toxicity, it must be remembered that all materials are toxic to a given environment, dependent on the dose level.

In contrast to other environmental impact categories considered in LCA, ecotoxicity is not based on an individual well-defined mechanism. Rather, there is a large collection of different basic mechanisms, with a common theme in the mechanisms being that they lead to toxic impacts on ecosystems. In comparison with other environmental impact categories ecotoxicity thus has the nature of a group category which includes all of the substances in a product system which can result in a direct impact on the health of ecosystems. As a consequence the list of substances from the product system which are classified as contributors to ecotoxicity is more comprehensive and less uniform than the corresponding lists for other environmental impact categories.

As a rule the ecotoxicological hazardousness of a substance is assessed on the basis of such impacts such as death, reduced growth or reduced reproduction. The list of known man-made ecotoxic impacts on the environment is extensive, and a few important examples are:

- Strongly toxic metals such as cadmium and mercury which are emitted from a large number of different processes and which cause acute and especially chronic effects of various kinds in the environment.

- Persistent organic substances such as PCBs (polychlorinated biphenyls), PAHs (polycyclic aromatic hydrocarbons) and dioxins, which accumulate in adipose tissue and cause various types of chronic effects.

- Organic substances which emulate the female sex hormone oestrogen in sensitive receptors in humans and animals, e.g. certain phthalic acid esters used in large quantities as plasticisers in PVC, and nonyl phenol, which is a stable degradation product of a group of commonly used detergents.

There is no unanimity within the environmental assessment of products on any coherent and operational method for a quantitative assessment of ecotoxic emissions on an equal footing with emissions which contribute to other environmental impact categories. It has therefore proved necessary to develop a method for the calculation of impact potentials for the contribution to ecotoxicity made by a product throughout its product system. The calculation of equivalency factors is based on considerations of the substance's potential fate in the environment and the effects on the ecosystem exposed to it.

- **Human Toxicity** (Hauschild and Wenzel, 1998)

  Human toxicity is defined in much the same way as ecotoxicity with the difference being substances under consideration are toxic to humans. Properties such as persistence and bioaccumulation potential are also considered in classifying a substance's human toxicity.

  Humans are exposed to the impacts of pollutants in the environment in a number of different ways. Direct exposure can occur via inhalation and ingestion of polluted groundwater, surface water or soil. Indirect exposure can also occur via ingestion of primary producers (plants) which have been exposed to pollution, and the ingestion of consumers (herbivores and carnivores) or their products (milk).

  The list of known man-made toxic impacts on humans is extensive, and in addition to the examples listed for ecotoxicity, volatile organic compounds, oxides of sulphur and nitrogen oxides which are emitted from combustion processes and which cause acute effects in persons with respiratory ailments will be included

  The toxic properties of each individual substance depend on a large number of different factors concerning the substance itself, the quantity emitted, the circumstances under which it was emitted and converted in the environment. As with ecotoxicity, in human toxicity there is no unanimity within the environmental assessment of products on any coherent and operational method for a quantitative assessment of toxic substances on an equal footing with emissions of substances which contribute to other environmental impact categories. It has therefore proved necessary to develop a method for the calculation of impact potentials for the contribution to human toxicity in the environment from the product throughout its life cycle. The calculation of equivalency factors is based on considerations of the substance's potential fate in the environment and effects on the human beings exposed to it.

- **Resource Consumption** (Hauschild and Wenzel, 1998)

  Resource consumption as an environmental impact category is concerned with assessing the sustainability of resource consumption patterns.

  In order to make an inventory of consumption of the various types of resources, it is necessary to follow the consumption of all materials and fuels back to extraction of the primary resources from nature, including the earth crust, the sea, the forest etc. All consumptions of primary resources in the product system must in principle be inventoried.

  Resource consumption is not classified based on the equivalency factors of a reference substance, but is normalised relative to the average annual consumption of one world citizen, thus expressing a product's resource in person-equivalents. Resource consumption is weighted by the World Reserves Life Index, WRLI, i.e. the product's normalised resource consumption is divided by the WRLI so that the scarcest resources are thus weighted most heavily and resource consumption is expressed as fractions of the known world reserves per person.

3.3.3.b Normalisation

To permit the comparison of the different environmental impacts for a system it is necessary to compare them against a common reference. Normalisation, which is an optional stage in LCIA has two purposes:

1. To provide an impression of the relative magnitudes of the potential impacts and resource consumptions.
2. To present the results in a form suitable for subsequent weighting and decision making

In normalisation, the impact potentials and resource consumptions which have been determined are compared to an impact which is common for all impact categories, and of which the consequences for the environment are known. In this way an impression is gained of which potential impacts are large and which are small, seen in relation to the known reference impact (Wenzel et al, 1997).

3.3.3.c Valuation.

Valuation is the process of assigning weighting factors to different impact categories based on their perceived relative importance as set by social consensus (Graedel, 1999). Weighting, which is also an optional stage in LCIA, would be necessary because normalisation assists in assessing the relative magnitude of the potential impacts but if the potential impacts of two different impact categories are equally large on normalisation, then automatically the potential impacts are seen to be equally serious. To be able to compare the potentials for the various impacts, an assessment must first be made of the seriousness of the impact categories relative to each other. The mutual seriousness of the impact categories is expressed in a set of weighting factors with one factor per impact category within each of the environmental groups. (Wenzel et al, 1997)

The weighting factor for an environmental impact must also reflect the possible consequences of the impact's effect relative to the other environmental effects. The seriousness of the impact categories depends on several characteristics of the environmental effect and the actual condition of the environment. Some of the characteristics are of a purely scientific nature and may be evaluated in the same way irrespective of the use to which the LCA will be put. Other characteristics are of a more normative or political nature, and depend on the context into which the LCA will enter. (Wenzel et al, 1997)

The methods of selecting weighting factors may be based on monetary methods, sustainability levels and the modelling of eventual environmental effects. The monetary models are based on avoidance/prevention/damage costs as the basis for relative comparison between the environmental issues. However, they may bear no relation to the extent of degradation caused by the use of emissions or resources. Sustainability levels are a long-term compromise between desirability and techno-economic feasibility. Levels of sustainability which are based on bio-geo-physico-chemical considerations, are no doubt the best, but are difficult to estimate. The methods of valuation through modelling of eventual effects are even more complex than defining scientifically sound levels of sustainability. (Sangle et al, 1999)

The societal weighting approach presupposes that weighting in LCA is normative and the relative importance of environmental issues is subjective in nature. Hence, the weighting of environmental issues would have to take into consideration the preferences, aspirations and values of citizens, based on which appropriate measures could be taken to meet their expectations. (Sangle et al, 1999)

3.4 STRENGTHS AND WEAKNESSES OF LCA AS AN ENVIRONMENTAL MANAGEMENT TOOL

The broad based nature of life-cycle analyses presents certain strengths and weaknesses in its application as a tool for environmental analysis. The strengths of LCA formed the basis for its selection as an environmental assessment tool for the comparison of the environmental performance of used oil recycling options in South Africa. However, it is also important to understand some of the weaknesses of LCA in order to define the limitations that must be recognised when interpreting the results of the LCA for decision-making purposes. Some of the strengths and weaknesses are discussed below.

3.4.1 Strengths of LCA as an Environmental Management Tool

- LCA's main advantage over other site-specific environmental management methods, such as environmental impact analysis, lies in broadening the system boundaries to include burdens and impacts in the whole life cycle of the product or process, rather than focusing on the emissions and wastes generated by the plant or manufacturing site only (Azapagic and Solberg-Johansen, 1998). LCAs may be used to support broad environmental assessments. The results of an inventory are important in understanding the relative environmental burdens between alternative processes or materials used to make, distribute or use the same product; and in comparing the environmental aspects of alternative products serving the same purpose. (Vigon et al 1994) The results from life-cycle analysis allow users to challenge and review the applicability of "conventional wisdom" on environmental management – for example the "reduce, reuse, recycle" hierarchy (Nash and Stoughton, 1994).

- A key application of a life cycle inventory is to establish a baseline of information on an entire system given current or predicted practises in the manufacture, use and disposition of the product or category of product. The baseline information is important for initiating improvement analysis by applying specific changes to the baseline system. (Vigon et al, 1994)

- A life-cycle inventory provides detailed data regarding the individual contributions of each step of the system studied to the total system. The data can provide direction to efforts for change by showing which steps require the most energy and other resources, or which steps contribute the most pollutants. This application is most important for internal industry studies to support decisions on pollution prevention, resource conservation and waste minimisation opportunities. (Vigon et al, 1994) The performance of life-cycle inventory analyses also reveals areas in which data for particular processes or regarding current practises are lacking or are of uncertain or questionable quality. (Vigon et al, 1994)

- Life-cycle analyses, when augmented by appropriate impact analyses, can provide information on the individual, simultaneous effects of many product attributes for organisations seeking product certifications. (Vigon et al, 1994) For the public policy maker, lifecycle inventories and impact analyses can help broaden the range of environmental issues considered in developing regulations or setting policies. (Vigon et al, 1994) Life-cycle analyses can also be used to educate industry, government, and consumers on the tradeoffs of alternative processes, products, materials and/or packages. The analyses can give industry direction in decisions regarding production materials and processes, and create a better informed public regarding environmental issues and consumer choices. (Vigon et al, 1994)

- The process of carrying out LCAs stimulates inter and intra-company communication and co-operation. (Jonson, 1996) LCA considers the environmental performance of a product across its entire life cycle and presents opportunities for companies to influence the environmental practises of other players in the life cycle chain. (Nash and Stoughton, 1994)

3.4.2 Weaknesses of LCA as an Environmental Management Tool

- LCAs can require significant labour hours to collect and verify data. Consequently they can be very costly to do. (White and Shapiro, 1993) In addition to this data collection is a tenuous area when performing LCAs as data may be unobtainable because it is of a confidential nature or because of lack of methodology or resources (time and money) for obtaining the data. Related to this may be perceptions of a lack of publicly accessible databases (Forbes, 1999)

- Methodologies differ widely in their treatment of missing data. In some studies it is not possible to determine which data comes from detailed sources and which data is derived

from general sources or based on professional judgements. It is also difficult to determine whether the uncertainty of data significantly affects the final results of a study. (Curran, 1993)

- Inventory data obtained during a life-cycle analysis must be translated to either positive or negative environmental impacts. The translating of life-cycle-inventory numbers into human health or ecological impacts is not well understood. The lack of a single method for comparing environmental impacts compounds the problem and in order to make a decision, some type of value judgement must be made. Results that may be subjective can thus be produced from the analysis. (Curran, 1993)

- LCAs have been used by companies to design products which are "kinder" to the environment, with the important benefit of a conferred marketing edge. Companies have not been reticent in claiming advantages for their products, but the claims are not always based on formal or sound studies. (Holloway, 1992) However, SETAC tried to minimise this weakness which was raised by Holloway (1992) by developing a "Code of Practise" which sought to eliminate uncertainty-especially when LCA is used as a tool for decision making. (Markovic, 1998)

Krozer and Vis (1998) have also reported that comparative LCAs have been contentious, with the consistency of data questioned by experts. In addition to this there continues to be professional doubts about the reliability of LCA. Krozer and Vis (1998) also highlighted some methodology imperfections of LCA and proposed ways of overcoming them. Some of the highlighted methodological imperfections are presented below:

- It is not always easy to generate inventories that have balanced input and output flows where detailed inventories are concerned, resulting in some LCA results being disputable.

- The allocation of environmental burdens in multiple flow streams is not always based on sound assumptions or accurate data. The nature of the assumptions and data quality influence the quality of results from an LCA.

- The impact categories presented in LCA have technical and normative limitations. In addition to this classifications are very sensitive with respect to data quality in the inventory and in instances where inventories are not specified well enough the results of the impact analysis may be significantly inaccurate. For example, inaccurate distinction or quantification between Cr^{3+} and Cr^{6+} flows may produce significantly inaccurate impact analysis results in an impact category such as human toxicity.

3.5 CONCLUSIONS

The purpose of this chapter was to present a summarised description of LCA methodology and procedure, beginning with goal and scope definition, Life Cycle Inventory (LCI) analysis and Life Cycle Impact Assessment (LCIA) procedures. This chapter was presented, primarily to provide the target audience unfamiliar with the practice of LCA with the description of the LCA process and to create a contextual basis for presenting the proceeding chapters of the thesis.

The strengths and weaknesses of LCA were also presented and as discussed in section 3.4 of this chapter, one of the main advantages of LCA is that it can support a broad based environmental assessment allowing for the environmental assessment of alternative system configurations achieving the same functionality. (Vigon et al, 1994)

It is this capacity of LCA that makes it an ideal tool to address the weaknesses of the current management philosophy for used oil in South Africa, as identified in Chapter 1.

The remaining chapters of the thesis are structured according to the procedure for carrying out LCA, as described in this chapter and illustrated in Figure 3.1. The goal and scope of the research will be presented in Chapter 4 while different aspects of inventory analysis will be discussed in Chapters 5 and 6 of the thesis. An interpretation of inventory results will be presented in Chapter 7 and a Life Cycle Impact Assessment of the inventory results will be presented in Chapter 8. Conclusions of the assessment will be presented in Chapter 9.

Chapter 4

Goal Definition and Scope

4.1 INTRODUCTION

In this chapter the goal and scope of the assessment will be defined. The used oil management options that have been selected were already presented in Chapter 2. This chapter formalises the goal and scope of the assessment, encompassing the definition of the target audience, the functional system boundaries and the data categories within which the assessment of the selected used oil management scenarios would be carried out.

This chapter will follow the structure for goal definition and scope presented in section 3.3.1 of Chapter 3.

4.2 GOAL OF ASSESSMENT

The goal of the environmental assessment of alternative options that may be used in the activity of managing used lubricating oil was to develop an assessment tool for comparing and evaluating the environmental performance of selected management scenarios in South Africa. The LCA based assessment tool for the evaluation of selected used oil management scenarios would integrate the environmental gains from site specific environmental improvements into a broad based environmental strategy that would seek to quantify the benefits of a used oil management option within the context of the entire lubricating oil manufacturing, use and re-use system. The LCA based assessment tool was to be constructed from data collected for selected used oil management options which would be integrated into a framework for assessing used oil management scenarios, allowing the results to be compared with those from elsewhere. The assessment tool would be used to draw first conclusions on the environmental performance of different options for used oil management, thus allowing strategic decision making while overcoming the limitations of the current fragmented approach.

4.3 THE TARGET AUDIENCE

This research is being undertaken in fullfillment of the Master of Science in Engineering degree awarded by the University of Cape Town. The work to be presented, as such should be of a quality meriting post graduate recognition.

The research is sponsored by the ROSE Foundation, and the ROSE Foundation and its contributing membership will be an intended audience.

The results of the research project should verify the hypotheses presented for the research and consequently be a tool for the South African lubricating oils industry's used oil management policy and decision making processes.

The research is to be structured in such a way as to allow a fundamental research follow-up on any opportunities that might be identified. The results of the research should thus be presented in a manner that future practioners on used oil research, will find the report of useful reference.

The target audience thus comprises of:

- Department of Chemical Engineering, University of Cape Town (Academic Staff and Post-graduate Researchers)
- The ROSE Foundation and its constituent membership
- Researchers in the Used Oil field

4.4 SCOPE OF PROJECT

The scoping phase sets out the procedural framework in which the life cycle assessment will be performed. As discussed in section 3.3.1, in presenting the scope of the LCA study the following components should be defined:

- the product/process or activity to be studied
- the choice of functional unit and reference flow
- the limitations and boundaries for all the unit processes over which the life cycle assessment procedure is to be employed
- description of data categories

4.4.1 Activity to be Studied

As evident from the goal definition, the LCA was to be carried out on the activity of managing used lubricating oil collected in South Africa. This activity incorporates the following:

1. Collection and storage of used oil

2. Utilizing the used oil in one of the following used oil management options
   - Burning for energy recovery without prior treatment.
   - Reprocessing for subsequent burning in an application utilizing the oil's energy value.
   - Reprocessing for other uses.
   - Re-refining of the used oil.

The following is a list of used oil management options that have been selected for analysis in this study. These used oil management options will be described in Chapter 5 of the thesis:

- Burning untreated used oil for energy recovery in an industrial furnace
- Burning untreated used oil for energy recovery in a cement kiln
- Burning reprocessed used oil in an industrial furnace
- Burning reprocessed used oil in a tunnel kiln brick-making furnace
- Re-refining used oil employing either configuration of the Revivoil Re-refining Process by IFP-Viscolube.

The activity may also impact on other aspects of virgin lubricating oil or heavy fuel oil production by:

- Potentially reducing the volume of crude or processed oil treated in the base oil refineries if re-refining of used oil is selected as a used oil management option.
- Potentially reducing the amount of heavy fuel oil (HFO) processed in the refineries for use as an inland fuel if used oil is burned for energy recovery in applications where it substitutes or supplements HFO.

Assessing the activity of managing used lubricating oil requires that a definition be proposed for used oil. This definition determines the material contaminants that may be found in the used oil, and consequently the processes that need to be employed in its treatment.

As already presented in Chapter 2, used oils will have a varied composition (see Tables 2.4 and 2.5) depending on the characteristics of the virgin oil and its use as well as the collection/handling process. During use contaminants may be introduced into the oil from the breakdown of the base oil and additive components as well as the introduction of organic matter, organometallic material, metal and inorganic particulates from equipment wear. In automotive applications lubricants degrade due to the relative high operating temperatures and contamination by engine wear products as well as combustion products.

In the research used oil was defined to have an average composition determined from the chemical contaminants analyses of over 230 samples of used oil collected from various used oil tanker loads in 1999. The average composition of South African used lubricating oil is given in Table 4.1.

Table 4.1 Averaged concentrations of contaminants for 233 samples of used lubricating oils collected and analysed in South Africa (1998 - 1999)

Contaminant	
Ash (wt %)	0.76
Water (vol %)	6.0
Sulfur (wt %)	1.01
	Averaged concentration (ppm)
Elements	
Aluminum	20
Arsenic	3
Barium	17
Boron	37
Calcium	1413
Chromium	4
Cobalt	0.5
Copper	29
Iron	155
Lead	1443
Lithium	1
Magnesium	179
Manganese	2
Molybdenum	7
Nickel	2
Phosphorous	623
Sodium	63
Tin	5
Titanium	1
Vanadium	1
Zinc	649

Source: Rose Foundation Data, 1999.

4.4.2 The Choice of Functional Unit and Reference Flow

A choice of function and functional unit consistent with the stated goals of the LCA had to be made.

As already stated, the goal of the study is to carry out a comparative LCA of an activity: The management of used lubricating oils. The function of this activity is to treat the collected used oil at the end of its useful life in a manner which utilises the oil's value (lubricant and/or energy utility) while keeping the environmental impacts at the end-use or processing locations to acceptable limits.

The functional unit forming the basis of this LCA is proposed as 1000kg of COLLECTED used lubricating oil.

4.4.3 Choice of Initial System Boundaries

The system boundaries that have to be defined for the scoping phase may be functional, geographical or temporal (the time frame in which material may be considered to be relevant to the study). The functional system boundary for the life cycle of the activity of managing used lubricating oil in South Africa is proposed in Figure 4.1. The system boundary forms the basis for selection of unit processes for which data was collected for building life cycle inventories in the research. The unit processes that form part of the life cycle of the activity of managing used oil are described in detail in Chapter 5 of the thesis.

In setting the initial functional system boundaries for the life cycle of the activity of managing used oil the following elements have been placed outside the system boundary:

- Loss of lubricating oil during use
- The additives manufacturing and lubricating oil distribution processes
- The production and distribution of refinery products other than lubricating base oils

The loss of lubricating oil during use has been placed outside the system boundaries because the activity of managing used lubricating oil will be carried out on the volume of collected oil. As indicated from the choice of the functional unit, the assessment will be based on a mass of COLLECTED oil, oils lost during the use stage of the life cycle will not be considered.

In the comparative LCA the activities carried out at the blending stage in the life cycle will be independent of the used oil management scenario chosen. Consequently the quantity of additives entering the blending system will remain constant and for this reason the burdens concomitant with the production of lubricating oil additives have been placed outside the system boundaries.

In placing the oil losses and additive production outside the system boundaries it would also have to be assumed that any re-refined base oil returned to blending will be identical to the new base oil, particularly:

- it will not require any different blending additives, and will be packaged in the same containers.
- it will behave identically during use, i.e. use-related losses will not change.

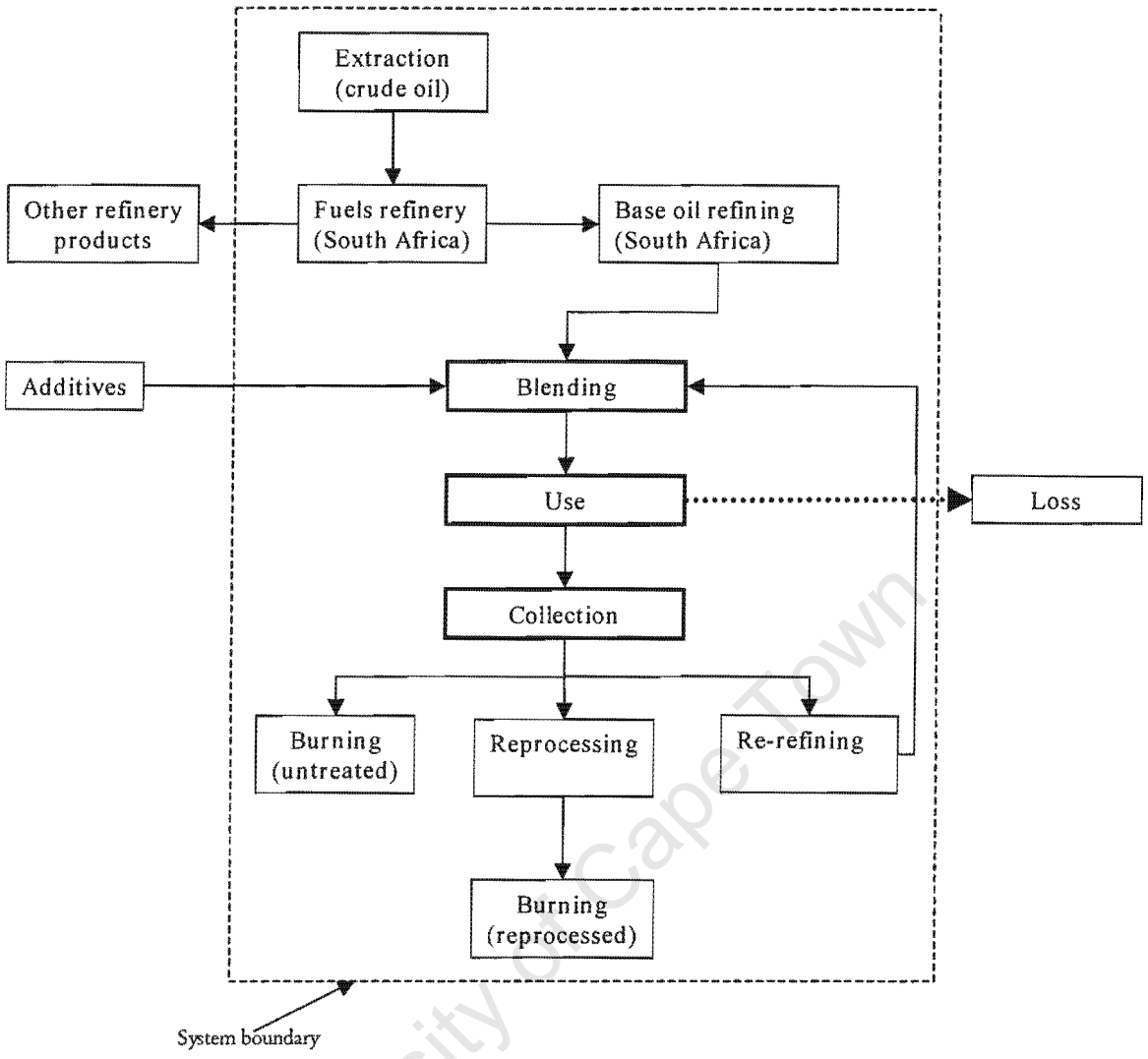


Figure 4.1 The functional system boundaries for life cycle on the activity of managing used lubricating oil in South Africa

Note: *The life-cycle steps in bold boundaries (extraction, blending, use and collection) can be left out in a comparative life cycle analysis as they are always the same, i.e. they are independent of the used oil management scenario chosen*

Co-products from the production of lubricating base oil have been placed outside the system boundary of the used oil management life cycle. The term co-product is used to define all output streams other than the primary product that are not waste streams and that are not used as raw materials elsewhere in the system inventory (Vigon et al, 1994). It must however be recognised that the base oil refineries in South Africa are part of a larger refinery flow scheme focused primarily on the production of light fuels such as gasoline, diesel and jet fuel. The crude distillation operations in the broader refinery flow scheme contribute a vacuum bottoms feed to the base oil refineries. The environmental and utility commitments associated with the vacuum bottoms feed were added to the base oil refinery system using a mass allocation procedure. The detailed description of the mass allocation procedure is given in Chapter 5 of the thesis.

Another flow path to be considered, though not presented within the system boundaries illustrated in Figure 4.1 are the avoided impacts that are concomitant with the used oil burning options in which the used oil substitutes heavy fuel oil. Heavy fuel oil (HFO), also called residual fuel oil can generally be classified as the low value residues derived from petroleum refining

processes focussed on producing high quality gasoline, kerosene, lubricants, greases, solvents and diesel oils. (Schmidt, 1986)

4.4.4 Description of Data Categories

The data used in building the Life Cycle Inventories for the used oil management life cycle in South Africa was to be obtained by the following means:

- Primary data was to be collected from the the unit processes in the used lubricating oil cycle. For example data for lube base oil manufacture would preferably be determined from averaged day to day production log sheets for unit operations in the refineries.

- Secondary data, such as published articles, studies and surveys were used.

- Relevant data modules as provided in LCA software would be used.

- Where data was not readiliy available clearly stated assumptions would be made.

Data quality requirements should be included for the following parameters

- Time-related coverage

  Data used in building the used oil life cycle inventory for South Africa where possible was to be generated from operations carried out within the last five years.

- Geographical coverage
  Geographical area from which data for unit processes should be collected to satisfy the goal of the study (e.g. local, regional, continental, global)
  The South African lubricating oils life cycle has life cycle stages covering both national and international boundaries. For example, the extraction stage of the lubricating oil life cycle may cover the Persian Gulf region from where South Africa obtains its crude oils. Data from the refining, blending, use and blending life cycle stages as defined in Figures 4.1 will have local or national geographical boundaries.

  The geographical boundaries of the study would be determined by the location of data for the process units and technologies to be considered in the research and these boundaries will be presented in Chapter 5 with the description of unit processes in the South African used lubricating oils life cycle.

- Technology coverage

  It was proposed that the best available technologies be considered in the study. Used lubricating oil treating technologies currently employed in South Africa were also to be considered, where data was available, as they could form a basis for improvement rating. It should be noted that the technologies being referred to include re-refining, reprocessing and burning technologies.

4.5 CONCLUSION

The goal and scope of the environmental assessment have been presented in this chapter and the process units that constitute the life cycle of the activity of managing used lubricating oil in South Africa were presented. These process units and the gathering of data will be described in detail in Chapter 5.

Chapter 5

Life Cycle Inventory (LCI) Data Gathering

5.1 INTRODUCTION

This chapter describes the processes, operations and recycling options that constitute the life cycle of the selected management options for used oil in South Africa. The methods used in data collection for the Life Cycle Inventories (LCI) are discussed and some representative data modules will be presented and discussed.

The description of the processes constituting the life cycles of the selected used lubricating oil management options will be presented within the framework of producing an LCI, as illustrated in Figure 3.2 in the thesis. Hence the processes in the used lubricating oil life cycle will be reviewed under the following LCI sub-stages:

- Raw material acquisition stage,
- Manufacturing stages,
- Use/Re-use and Maintenance stages,
- Recycling and Waste management stage.

As explained in Chapter 4 and illustrated in Figure 4.1, the results of a comparative assessment of the selected used oil management scenarios will be independent of the environmental burdens associated with the lubricating oil blending, used oil collection and used oil storage. For this reason data modules for these stages in the used oil management system boundary were omitted in the assessment and will not be described in this chapter.

The construction of an inventory for a process involves the quantification of product and co-product flows, utilities, emissions and wastes, process maintenance and product quality control material flows. The process of collecting data for each LCI sub-stage will also be described with reference to assessing the following aspects:

- Assessment of data sources and their reliability,
- Assessment of data quality. This will involve the consideration of data precision, completeness and representativeness,
- The presentation and justification of any assumptions made on areas of incomplete or unreliable data,
- Discussion of the allocation of flows and releases.

The life cycle paths and the environmental performance of used oil management options will be reviewed within the context of the life cycle inventory analysis procedure. This is to enable readers without adequate understanding of LCA to understand the standard methodology and procedure employed in Life Cycle Inventory analysis.

5.2 RAW MATERIAL ACQUISITION

In the used lubricating oil life cycle raw material acquisition is the extraction and transportation of crude oil to the point of refining.

The commonly held hypothesis about the origins of crude oils is the fossil fuel theory, which states that the crude oils are as a result of the decomposition of plant and animal matter in salt water. According to the theory, the remains of dead plants and animals were collected in sedimentary basins, especially in places where rivers dump silt into the sea. Over time they were buried and compressed. Under these conditions the organic matter transformed into tar-like molecules called kerogen. As the temperature and pressure increased the kerogen gradually transformed into the complex hydrocarbon molecules which are the basic constituents of crude oil. (Stachowiak and Batchelor, 1993)

Crude oil occurs in ground pockets or traps and is discovered by prospectors using geological and geophysical methods. Oil wells are drilled from a tower known as an oil derrick, which supports the basic equipment. A cutting tool is attached to a length of steel piping and used to drill for the oil. As the hole deepens additional lengths of drill pipe are added. If oil is present it is brought up to the surface, in a controlled manner. Special equipment consisting of high pressure valves and piping, is placed over the well-head like a cap. With this equipment known as a "Christmas Tree", the flow of oil can be carefully controlled and pumped through kilometres of pipeline to the waiting tankers. After loading aboard an oil tanker, the crude oil is transported to an offloading point near the refinery, where, with the aid of the ship's pumps, it is transferred to the refinery tanks along a pipeline. From here it is pumped into the refinery itself. (Caltex, 1981)

Base oil refining in South Africa is carried out at two refineries located in Durban. The base oil refineries process long residue feedstock as well as crude oils coming predominantly from Iran and Kuwait. In Durban the crude oil, which is delivered by oil tankers, is discharged through an offshore Single Buoy Mooring facility and product is transferred to storage tanks. (Mbendi, 2000; Sapref, 1999)

5.2.1 Environmental Concerns During Crude Oil Extraction and Transportation

When crude oil is examined to determine its chemical composition it is found that it consists mainly of compounds of carbon and hydrogen, called hydrocarbons, and small quantities of sulphur, oxygen, nitrogen and inorganic salts and relatively smaller quantities of metals. (Sequeira, 1989) Owing to the nature of crude oil, the extraction and transportation of crude oil to the refinery contribute to air, water and ground pollution to various extents depending on the handling and processing methods. The greatest environment threat, as perceived by the public is the spilling of crude oil from tankers into the marine environment during transportation, or offshore extraction. When crude oil or petroleum products are released into the marine environments they are immediately subjected to a variety of weathering processes such as:

- spreading and drift
- evaporation
- dissolution and advection
- dispersion of whole oil droplets into the water column
- photochemical oxidation
- water-in-oil emulsification
- microbial degradation
- adsorption onto suspended particulate material
- ingestion by organisms
- sinking and sedimentation

The oil composition and the position of the release greatly influence the relative magnitudes of each of the above named processes, as well as affecting relative changes in oil composition and associated rheological properties due to physical/chemical weathering. (Doerffer, 1992) The impacts of oil on the marine environment include (Doerffer, 1992):

- Physical contamination of water bodies
- Tainting of fish and crustaceans
- Tainting of marine mammals
- Effects of oiling on water birds
- Contamination of coral reefs, beaches, salt marshes and mangroves

5.2.2 Data Collection for Crude Oil Extraction and Transportation

Owing to financial and time constraints it was not considered feasible to collect primary data for crude oil extraction operations in the Middle East which supply crude oils to the base oil refinery operations in Durban.

Life Cycle Inventory (LCI) data on the extraction stage of the used lubricating oil life cycle from the Ecobilan software data module for crude oil extraction was used. Information on the data module indicates the following:

- Geographical source of crude: Middle East
- Average transportation distance: 4800 nautical miles by 100 000 metric ton tanker plus 7900 nautical miles by 250 000 metric ton tanker
- Data obtained over 12 months period during 1989 to 1991
- Sources: Eco-Profiles of the European Plastics Industry (PWMI, May 1993) Report on Olefin sources pp. 8.

It has been assumed that this data is collected from extraction and transportation operations which are representative of the sources of the Middle East crudes processed in the South African base oil refineries.

5.3 MATERIALS MANUFACTURING: CRUDE OIL REFINING TO PRODUCE LUBRICATING BASE OILS

The manufacturing stage of lubricating oil consists essentially of two main sub-stages. The first sub-stage is refining which represents materials manufacture in the life cycle inventory, and covers activities that are required to process raw material into a form that can be used to fabricate a particular product. The second manufacturing sub-stage is the blending operations. In life cycle inventory definition this sub-stage would be taken as product fabrication and covers process steps that use the manufactured materials to fabricate a product ready to be packaged. Filling, packaging and some parts of the distribution process are also carried out at the blending facilities.

5.3.1 Refining of lubricating base oils in South Africa

Base oil refining in South Africa is carried out at two refineries located in Durban. These are the Samco base oil refinery which is jointly owned by Shell and BP, and the Safor base oil refinery which is owned by Engen Petroleum, Caltex and Total. The Samco is downstream of the Sapref fuels refinery and has a capacity of 175 ML/a (155 tonnes/a). Safor, which is downstream of the Engen refinery (Engref), has a capacity of 165 ML/a (145 tonnes/a). However, the two

refineries' capacity does not produce all the base oil grades required in South Africa and imports of various speciality base oil grades are made. (Mbendi, 2000)

Both the Samco and Safor base oil refineries have the basic refinery flow scheme, and processing units shown in Figure 5.1. The initial step of refining a crude is to separate the crude into a series of narrow boiling range fractions which are the raw stocks for the various products to be made. After water, salts and sediments have been removed by preliminary processing, this initial separation is carried out in the crude distillation unit (CDU) which operates under atmospheric conditions (also called the atmospheric distillation tower). The main lubricating oil fractions are obtained from the residue of atmospheric distillation, which is further distilled under reduced pressure conditions in the vacuum distillation unit (VDU). The design and operation of the VDU is of utmost importance in the manufacture of lube base oils because distillate properties, particularly boiling range and feedstock purity, can have a significant effect on processing response in the lube refining, dewaxing and finishing units as well as the quality and yield of the finished base oil. (Sequeira, 1993)

Following the fractionation processes, further treatment is necessary before the base oils are suitable for final product blending. The treatment methods that may be employed are shown in Table 5.1.

5.3.2 Refinery Utility Requirements and Environmental Controls

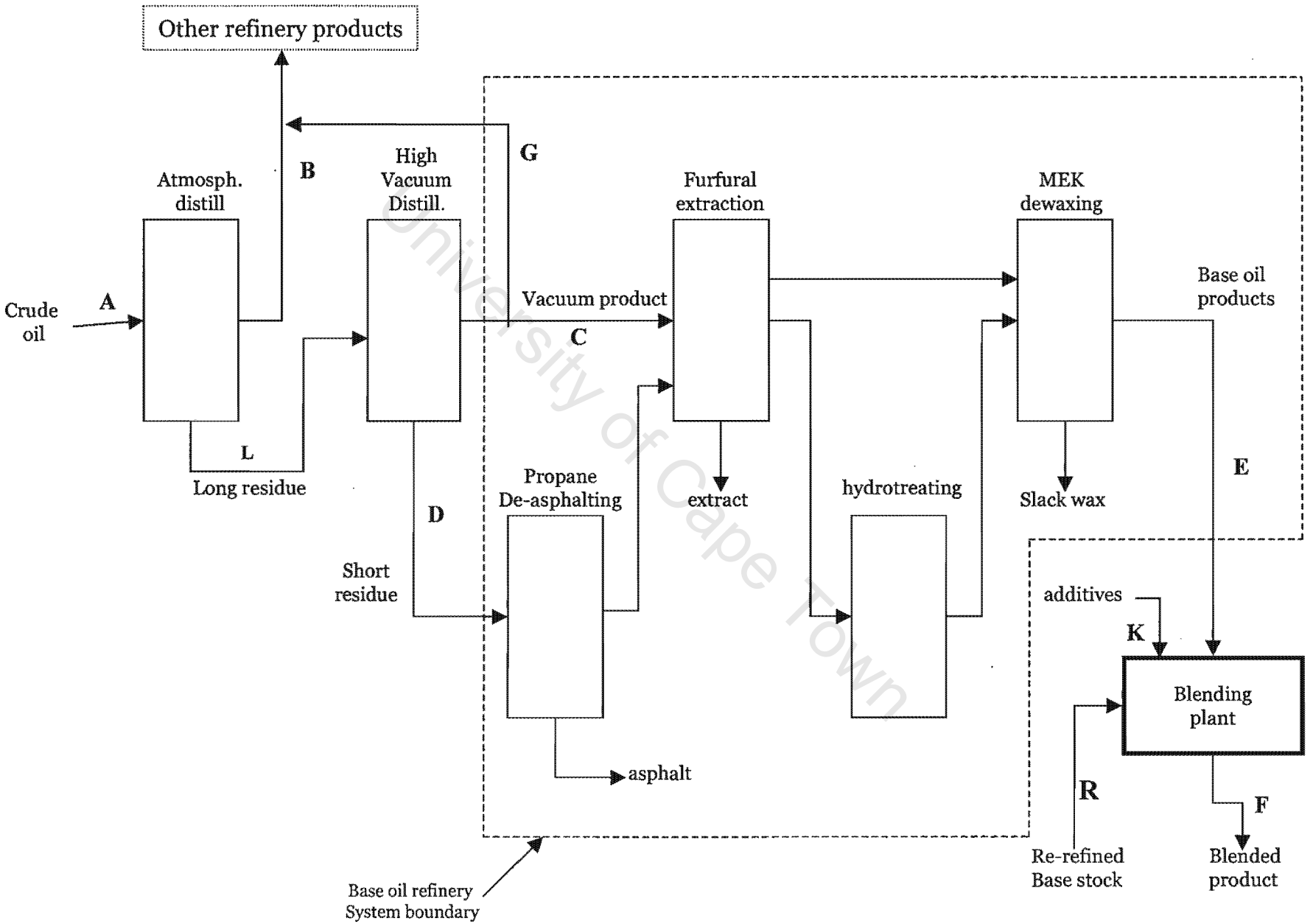
Refinery operations are energy intensive with large energy requirements for distillation, stripping, preheating and other treatment processes. Electrical energy is normally a relatively small contribution to the refinery's total energy demand (less than 10% for the South African lubricating base oil refineries) and is used for fluid pump motors and other moving equipment. The energy requirements are largely met by burning fuels produced within the refinery system, with process steam and direct firing operations having their energy provided from the burning of products from the fuels refinery.

The refineries burn large quantities of fuels and use a large quantity of water for steam production, and cooling purposes. It is therefore inevitable that the refineries will discharge certain materials into the air and have to dispose of wastewater. All South African refineries were built on grass-root sites well away from densely inhabited areas. However, over time urban suburbia has spread to the point where the refineries are now surrounded by habitation. The communities surrounding the refineries have over the years put increasing pressure on the refineries to commit to pollution abatement. Although air and water pollution abatement is of prime importance, the refineries also pay close attention to avoiding or minimising nuisances caused by noise or odour.

The refineries burn two types of fuels i.e. residual fuel oil and fuel gas. The gas is essentially sulphur free, but the residual fuel oil contains varying amounts of sulphur with a product specification limit of 3.5 % (m/m), distributed as MFO 150 cSt. (Sapref Product Quality Report, 1999)

Modern furnace equipment and operational control is such that black smoke and soot are not seen during normal conditions. Furnaces operating on sulphur-free fuel gas only, release carbon dioxide, nitrogen, inerts and water vapour as well as relatively small amounts of oxides of nitrogen and carbon monoxide. However, when fuel oil is used, sulphur combusts to sulphur dioxide-which is also invisible, and to a lesser degree sulphur trioxide. The faint blue smoke, which is visible at the top of the stack towers, is mainly due to sulphur trioxide. Sulphur dioxide, although invisible can, when it reaches ground level, damage certain plants and cause irritation of respiratory organs of people and animals. There is therefore strict limitation and monitoring of the quantities of sulphur emitted by the refineries. It is up to refinery operation to optimise

Figure 5.1 Basic refinery flow scheme for lube base oil production



between burning fuel oil and fuel gas so as to remain within the sulphur emission limits. (Caltex, 1981; Sapref, 1999)

Table 5.1 The main treatment processes for lubricating oils in base oil refineries in South Africa

Process	Purpose
Deasphalting	To remove asphaltic matter, particularly from mixed-base short residues, which would separate out at high and low temperatures, and block oil ways. Liquefied propane is used as a solvent in the deasphalting process.
Solvent extraction	To remove highly aromatic materials to improve viscosity index. Solvent extraction is carried out in the Furfural Extraction Unit where furfural extraction is used to dissolve aromatics and to improve the viscosity index, and to improve the oxidation stability of the lubricating oils. Due to its aromatic structure furfural is capable of selectively dissolving other aromatics. (SAPREF, 1999)
Dewaxing	To remove waxy materials from paraffinic and mixed-base oils to prevent early solidification when the oil is cooled to low temperatures, i.e. to reduce pour point. Dexawing is carried out in the Methy-Ethyl ketone (MEK) Toluene Dewaxing Unit where the removal of waxy compounds is achieved by mixing the waxy raffinate with MEK-toluene mixture. The mixture is chilled to -20°C, and the crystallized wax is removed under vacuum in rotary drum filters. (SAPREF, 1999)
Hydrotreating	To reduce sulphur content and, according to severity, to reduce aromatic content by conversion to naphthenes.

Source: Sapref Technical Oil Cooking Course Handbook, 1999

Water is used at the refineries for raising steam and as non-contact cooling water. Only a small volume of water in stripping operations comes into direct contact with process streams. Storm water runoff from process areas is also a significant source of wastewater. As a result of the large volume of cooling water required, most of the cooling water is re-used and a small proportion of cooling water is purged, and the volume maintained constant by a fresh water make-up stream.

The wastewater leaving the refineries entrains some oil, and other contaminants such as sulphides, ammonia and phenols. This sour water has to be cleaned at a treatment plant before it is discharged by pumping out to sea. There is a government permit giving permissible levels of the various constituents of this water as well as a maximum quantity.

5.3.3 Data Collection for the Refinery Operations

Data used for building the refineries inventory was collected using a combination of the three basic data collection approaches which are:

- Primary data collection, where the raw materials producer directly describes how they produce their product and provides as much of the necessary data as possible.
- Secondary data, where published data such as articles, studies, and surveys are used.
- Assumptions where the analyst or producer makes assumptions about the parameters of the products use.

Two University of Cape Town third year Chemical Engineering students, attached to Samco and Safor refineries, respectively, carried out the process of gathering data for the refinery operations at the Durban refineries between December 1999 and February 2000.

The data collected for both lube base oil refineries was collected from day to day operation log sheets compiled between January 1998 and December 1999. In addition to the data compiled by the student at the Samco refinery, data was made available from a detailed operations survey carried out on all aspects of the base oil refinery's operations, called the Solomon's study compiled for the year 1998. Data on effluent leaving the refinery although available, was variable and its use has been supported by assuming pollution specifications based on maximum permissible concentrations as provided by the Department of Water Affairs, South Africa and the city drainage by-laws for large works (>25Ml/d), as specified by the Durban city council (see Appendix B). Data used in compiling the life cycle inventories for the refineries is thus based on averaged data for the refineries for the period between January 1998 and December 1999. The data for Samco and Safor refineries was further processed to give an industry average LCI database for South African lubricating base oil refineries.

The process of aggregating collected data involved processing and averaging data for two refinery operations which was variable in quality. In some data categories, data from one refinery was better defined; in other data categories one refinery did not have any data at all. In cases where the variability in data quality was significant, the data of a higher quality from one of the refineries was used to represent the industry average and in cases where data was not defined for both refineries assumptions were made.

Process, utilities and emissions data that was provided for the refineries is of a proprietary nature and was provided with the strictest confidentiality. However, a tabulated data module showing the main flows for industry average data for base oil refining is given in Tables 5.2 and 5.3. The flows in the module are normalised to the production of 1000kg of lubricating base oil.

5.3.4 Allocation of environmental burdens for the base oil refining processes

Allocation is the process of assigning to each of the functions of a multiple function system only those environmental burdens associated with that function (Azapagic and Clift, 1999). The problem of allocation arises in the base oil refinery system because the refinery system produces an array of products, other than lubricating base oil (light fuels from the fuels refinery system and waxes, extracts and asphalt in the base oil refinery system boundaries)

According to ISO 14041 (SABS ISO 14041, 1998) the allocation problem must be solved by using physical causation which reflects the underlying physical relationships among the functional units. Where physical relationships cannot be established, other relationships including the economic value of the functional outputs can be used.

In allocating burdens for the lube base oil refinery system two methods of allocation were used each covering the separate sub-system boundaries for the refining process as illustrated in Figure 5.1:

- An economic value based allocation was used for the base oil refining sub-system.
- A mass based allocation formula was used for the upstream atmospheric and vacuum distillation units, which form part of the broader light fuels refinery.
- The impacts from crude oil extraction and transportation were also allocated using a mass based formula.

Table 5.2 Data module for industry average data representing the atmospheric and vacuum distillation units. (Data normalised for 1000kg of lube base oil product in the Base oil refinery)

material	quantity	unit	Comment
INPUTS			
Crude oil (A)	13872	kg	
Steam	422	kg	
Fuel oil	138	kg	
Fuel gas	163	kg	
Electricity	524	MJ	
OUTPUTS			
Short residue (D)	1407	kg	
Vacuum product (C)	2042	kg	
Other refinery products (G+B)	10333	kg	
WASTE FLOWS			
Waste water	600	kg	Based on effluent specifications for Durban for large works (>25Mlit/day) see Appendix 1
(w) Unspecified oils and greases	18	g	
(w) sulphates	150	g	
(w) sulphides	0.6	g	
(w) chlorides	600	g	
(w) fluorides	3	g	
(w) phenols	6	g	
(w) suspended solids	1200	g	
(w) total dissolved solids	600	g	
(w) copper	30	g	
(w) zinc	30	g	
(w) lead	12	g	
(w) total chrome	12	g	
Flue Gas	4312	kg	Calculated from specified concentrations for refineries
(a) CO_2	873	kg	
(a) CO	423	g	
(a) NO_x	378	g	
(a) SO_2	9.1	kg	
(a) SO_3	0.7	kg	
(a) particulates	534	g	

Table 5.3 Data module for industry average data representing the Base oil refineries in South Africa. (Data normalised for 1000kg of lube base oil product from the Base oil refinery)

material	quantity	unit	Comment
INPUTS			
Short residue	1407	kg	
Vacuum residue	2042	kg	
H_2 rich fresh gas	137.6	kg	
Propane	3.2	kg	
Toluene	1.1	kg	
Furfural	1.3	kg	
MEK	1.2	kg	
Cooling water	1798	kg	
Steam	2104	kg	
Fuel oil	46	kg	
Fuel gas	94.7	kg	
Electricity	606	MJ	
OUTPUTS			
Lube oil	1000	kg	
Asphalt	982	kg	
Extracts	898	kg	
Slack wax	356	kg	
Off spec slops	5.7	kg	
WASTE FLOWS			
Waste water	907	kg	Based on effluent specifications for base oil refinery
(w) Unspecified oils and greases	18.2	g	
(w) sulphides	7.2	g	
(w) phenols	4.8	g	
(w) total dissolved solids	68	g	
(w) furfural	3.7	g	
Flue Gas	1421	kg	Calculated from specified concentrations for refineries
(a) CO_2	291	kg	
(a) CO	147	g	
(a) NO_x	105	g	
(a) SO_2	3	kg	
(a) SO_3	0.24	kg	
(a) particulates	178	g	

5.3.4.a The value based allocation of burdens for the base oil refinery system

The primary focus of the base oil refinery plant is to process incoming oils to produce high quality lube base oils. In the process of treating the various flow streams other lower value co-products are yielded (wax, asphalt, extracts). A simplified system showing the main material and utility flows for the base oil refinery plant is given in Figure 5.2. The typical yield of base oil from the feed stream "processed oil" is 30 % on a mass basis.

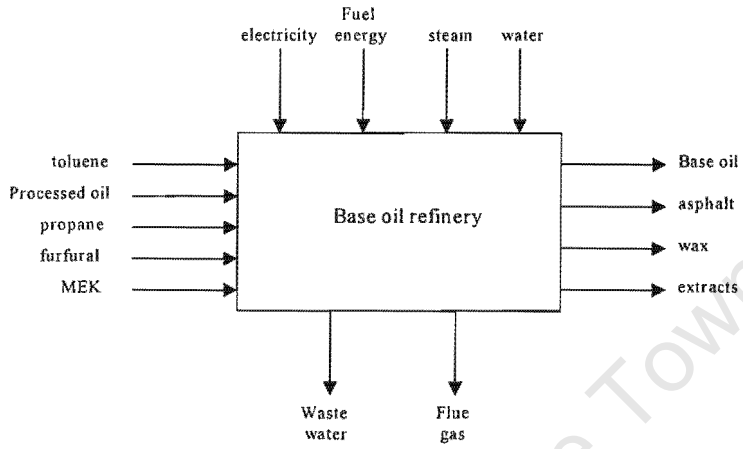


Figure 5.2 The major material and utility flows for the base oil refinery plant

For the system shown in Figure 5.2 it was assumed that base oils contribute 80 % of the total economic value of the product spectrum. Using this economic value based allocation, 80 % of the environmental burdens concomitant with the base oil refinery plant would be allocated to base oils. The allocation of environmental burdens of a flow (i) to base oil for the base oil refinery was effected by using the formula;

$$\begin{pmatrix}\text{environmental}\\ \text{burden}\end{pmatrix}_i = 0.8 * \begin{pmatrix}\text{total base oil}\\ \text{refinery environmental}\\ \text{burden}\end{pmatrix}_i$$

Even though base oil products are about 30 % by mass of the base oil refinery output an economic value allocation method giving a disproportionately high allocation value to base oil was selected because the outcome intended from the severe multiple processing stages of the base oil refinery is to produce a high quality, high economic value base oil product.

The influence of adjusting this economic value of the base oils will be assessed in Chapter 7 using a sensitivity analysis tool in the LCA computational model.

5.3.4.b Mass based allocation of burdens for the distillation units

The base oil refineries are part of a larger refineries system focused primarily on producing light fuel products such as gasoline, diesel and jet fuel. A mass based allocation of environmental burdens was used for process flow streams from the fuels refinery system that go into the base oil refinery plant. The basic allocation formula, using flow names given in Figure 5.1, for the allocation of environmental burdens of a flow (i) for the distillation units is given below.

$$\begin{pmatrix}\text{environmental}\\ \text{burden}\end{pmatrix}_i = 0.8 * \left\{ \begin{pmatrix}\text{total atms. distil}\\ \text{environmental}\\ \text{burden}\end{pmatrix}_i + \begin{pmatrix}\text{vac. distil}\\ \text{environmental}\\ \text{burden}\end{pmatrix}_i \right\} * \left(\frac{M_C + M_D + M_{\text{fuel gas}}}{M_A} \right)$$

A mass based allocation of environmental burden for the distillation units was used because the products from the units are intermediate flows to other refinery processing stages, and the economic value of these sub-processed products would be difficult to ascertain.

5.3.4.c Allocation of crude oil extraction burdens

Burdens associated with crude oil extraction and transportation need to be allocated between the different refinery products, of which base oil is but one. In connection with the re-refining of used lubricating oil, the question must also be asked how this would impact on the crude oil extraction phase of the life cycle.

In their LCA study to compare re-refining to burning of used oil, Vold et al (1995) assumed a relationship in which the quantity of base oil produced in a refinery is equal to the quantity of crude oil processed, and based on this relationship the selection of the re-refining option directly reduces the quantity of crude processed. These relationships for the Norwegian study (Vold et al, 1995) are illustrated in Figures 2.8 and 2.9 in Chapter 2.

A different approach is taken here. The relationships that have been assumed to be relevant to the South African refineries and the influence of recycling will now be discussed with specific reference to the allocation methods. Figure 4.1 and Figure 5.1 will be used in this discussion to investigate the possible quantitative relationships that exist between the amount of base oil produced and the crude quantity of crude oil processed as well as investigating the influence of recycling the re-refined base oil on the system.

Figure 5.1 is taken to represent, in greater detail, the upstream sub-systems of the used oil management life cycle in Figure 4.1 consisting of crude oil processing, base oil refining and blending with R representing the recycled quantity of re-refined base oil.

If it is assumed that the output from the blending plant, F, is fixed then recycling a quantity of base oil R results in the quantity of base oil entering the blending plant, E, reducing to (E-R). The mass of additives used, K, remains constant.

On the basis of a mass balance analysis the mass of processed oil entering the boundaries of the Base Oil Refinery will reduce by a factor (E-R)/E = α, and the mass of processed oil entering the base oil plant becomes,

$$\alpha * (C+D)$$

It can thus be concluded from the presented relationships that the recycling of re-refined base oil will reduce the quantity of processed oil refined to base oil in the Base Oil Refinery, and consequently also reduce the environmental burdens associated with the base oil refinery. It must however be recognised that there will be practical limitations to the implementation of this scenario for Base Oil Refinery since there is a minimum inflow of (C+D) for which the refinery can operate economically.

The mathematical relationship presented for the base oil plant and the recycle stream, R, cannot be extended to the atmospheric and vacuum distillation units. It will be assumed that in practice reducing the quantity (C+D) entering the Base Oil Refinery will not reduce the quantity of crude, A, being processed as the purpose of the broader refinery system to which the distillation units

are attached, is to derive as high a yield of light fuel products as possible from each barrel of crude processed. The reduction of the quantity of oil being processed in the base oil refinery, (C+D) would thus be effected by diverting a larger quantity of the vacuum product, G to making other refinery products while crude intake, A remains constant.

The above assumed relationship between the distillation units and base oil plant also implies that the quantity of crude oil processed, A remains constant regardless of whether base oil is recycled or not. However, the assumed relationship will influence the allocation of environmental burdens associated with crude extraction differently for the system with and without recycling.

In allocating the environmental burden, for a flow (i) associated with a selected used oil management option in which there is no recycling of base oil the following mass based allocation formula was used:

$$\begin{pmatrix}\text{enviro}\\ \text{burden}\\ \text{crude extraction}\end{pmatrix}_i = 0.8 * \left\{\left(\frac{M_C + M_D + [M_{\text{fuel gas}}]}{M_A}\right)\right\} * \begin{pmatrix}\text{total}\\ \text{enviro}\\ \text{burden}\\ \text{crude extraction}\end{pmatrix}_i$$

In allocating the potential environmental impacts associated with the recycling of a quantity of base oil, R it will be assumed that the recycling of R will result in a consequent decrease in the quantity of processed oil treated in the base oil refinery. The quantity of process oil that is diverted, H will thus be given by,

$$H = (C+D) - \alpha(C+D) = (1-\alpha)(C+D)$$

Reducing the flow of processed oil, C+D to the base oil refinery so that the equation for the allocation of potential environmental impacts associated with crude oil extraction in a system where base oil is recycled will be given by:

$$\begin{pmatrix}\text{enviro}\\ \text{burden}\\ \text{crude extraction}\end{pmatrix}_i = 0.8 * \left\{\left(\frac{\alpha(M_C + M_D + M_{\text{fuel gas}})}{M_A}\right)\right\} * \begin{pmatrix}\text{total}\\ \text{enviro}\\ \text{burden}\\ \text{crude extraction}\end{pmatrix}_i$$

The possible environmental impacts to the broader refinery system that would arise from the recycling of base oil would require comparing the marginal difference between the reduction of environmental burdens that is gained from reducing the quantity of fuels refinery product treated in the Base Oil Refinery and the increased environmental burdens resulting from increasing the quantity of intermediate products (B+G+H) that would be used in processing other refinery products. The process of determining potential environmental impacts of making other refinery products is outside the system boundaries stated in the scope of the study in Chapter 4. Moreover, determining the fate of the diverted oil, H is complicated, requiring an analysis of the entire fuels refinery system, a process that could not be achieved within the time frame set for the research.

5.4 MATERIALS MANUFACTURE: HEAVY FUEL OIL MANUFACTURE AND BLENDING

It was considered important and necessary to gather data for the manufacture and combustion of heavy fuel oils (HFO) because used lubricating oil utilised in burning options will normally substitute or supplement the use of heavy fuel oil. Hence, there is a quantifiable potential environmental gain associated with the burning of used oil, in the form of avoided impacts from HFO production and combustion.

HFOs produced in South Africa for inland fuel consumption have product specifications presented in Table 5.4

Table 5.4 Specifications for MFO 150 cSt

PROPERTY	UNITS	Method	MIN	MEAN	MAX
Density @ 15oC	kg/l	D.1298	0.9873	0.9891	0.9907
KV @ 50oC	cSt	D.445	109	135	150
Sulphur content	% (m/m)	D.2622	2.9	3.2	3.5
Pour point	°C	D.97	-21	-12	-6
Calorific value	MJ/kg	CALC		42.5	
Flash point	°C	D.93	67	73	79
Water	% (v/v)	D.95	0.10	0.15	0.40
Sediments	% (m/m)	D.473		NIL	
NEUT VALUE: Strong acid No. Total acid No.	(mg KOH/g)	D.974		 NIL 0.8	
Carbon residue (MCRT)	% (m/m)	D.4530	16.0	17.6	18.9
Aluminium	mg/kg	IP 377	2	12	25
Silicon	mg/kg	IP 377	4	22	45
Al + Si	mg/kg	IP 377	6	34	70
Ash		D.482	0.01	0.03	0.06
STABILITY: Existent dry sludge Accelerated dry sludge	% (m/m)	 IP 375/ IP 390	 0.01	 0.03 0.03	 0.05
Vanadium	mg/kg	IP 285	124	158	205
Sodium	mg/kg	SMS 1650		13	
CCAI		CALC	850	855	858

Source: SAPREF Product Quality Report, 1999

5.4.1 Heavy Fuel Oil Manufacture

Heavy fuel oils are produced from the crude refining process, primarily designed to produce high yields of high grade gasoline, kerosene, lube oils and other products. Many petroleum products receive additional treatment to remove many of the impurities and unwanted products, but fuel oils do not. Fuel oils receive the least attention of any of the refined products, because they do not need to meet the rigid specifications of the other types of oils.

Modern refining methods basically produce two types of oil – straight-run and cracked. Formerly all oils were straight run, but today most oils are cracked to increase the yield of lighter, higher value products. Straight-run processes are the distillation processes in which the crude oils are put through to separate the light oil products from the heavy oil products. Straight run processes

yielding heavy fuel oils are the atmospheric and vacuum distillation units already described in section 5.3.1. The distillation processes produce No. 2 and Nos. 5 – 6 fuels in the following respective boiling point ranges: 163 – 399°C, 316 – 538°C.

After the initial distillation processes, further refining can be accomplished using either of three of the most important cracking methods: thermal cracking, catalytic cracking, or visbreaking. The application of these cracking methods has allowed modern refinery operations to increase the average distillate yield to 79 %. Primarily, this has been at the expense of the residual oils whose yield had dropped to 9 %. (Schmidt, 1986)

5.4.2 Environmental Concerns Regarding Heavy Fuel Oils Manufacture and Combustion

The environmental concerns associated with the manufacture of heavy fuel oils are in general the same as the environmental concerns associated with the production of the entire range of refinery products. These environmental concerns have already been discussed in section 5.2.2 of this report.

The burning of heavy fuel oils in industrial applications is however, a major environmental concern as all fuel oils contain a certain amount of organic sulphur. (see Table 5.4 for sulphur specifications for South African fuel oils) The sulphur content depends on the source of the crude, the modes used in processing and treating the various components.

One of the critical problems caused by sulphur in fuel oils is the lowering of ambient air quality by pollution. The combustion converts the sulphur to sulphur dioxide (SO_2)- an irritating gas, which is emitted from the smoke stack, contaminating the atmosphere. During combustion in excess air, sulphur burns to form both sulphur dioxide and sulphur trioxide. These gases when exposed to moisture, form sulphurous and sulphuric acids. In an effort to reduce the emission of SO_2, most countries have introduced maximum limits for fuel sulphur or compulsory fuel gas purification. These limits vary widely from one area to another. In highly industrialised areas where the atmosphere is generally heavily polluted, allowable SO_2 emission from combustion is low. In open country areas or less industrialised areas, the allowable rate is higher. Total SO_2 emissions are almost entirely dependent on the sulphur content of the fuel, and are not affected by furnace size, burner design or grade of fuel being fired. On average, more than 95 % of the fuel sulphur is converted to SO_2, with about 1 – 3 % further oxidised to SO_3. (Schmidt, 1986; Sapref, 1999)

The sulphurous and sulphuric acid products formed at the end of the combustion process have a deteriorating effect upon the combustion equipment and some of the manufactured products. These acids, in contact with any exposed metal, such as boiler shell, tubes and surfaces, will cause corrosion. (Schmidt, 1986)

The complete combustion of heavy fuel oils is best achieved at high temperatures (>800°C) in excess air. At these high temperatures the nitrogen of the combustion air as well as that in the fuel may oxidise to nitric oxides (NO_x). The rate of formation of NO_x is influenced by the temperature and the oxygen available in the combustion zone. Lower flame temperature and excess air reduces the generation of NO_x, however, these impacts can result in increased yield of incomplete combustion products. Nitric oxides are green houses gases with hundreds of times more damaging impacts than CO_2. (Basu et al, 1999) They are also reactants in photochemical smog formation and are toxic/irritants to humans. (Hauschild and Wenzel, 1998)

5.4.3 Data Collection for Heavy Fuel Oil Manufacturing Operations

Heavy fuel oils are produced from all refinery operations operational in South Africa (Caltex Refinery, Engen Refinery, Natref Refinery and Sapref Refinery). Primary inventory data for the manufacture of heavy fuel oils was collected at Engen Refinery in Durban and at Caltex Refinery in Cape Town. This data was composed of material flows and process utility requirements obtained from logged day-to-day production provided by the Process Engineers managing the operation of the various refinery units that yield heavy fuel oils. Data was collected for the two refineries, based on operations between January 1998 and December 1999 with the intention of aggregating it to produce a data module assumed to be representative of the heavy fuel manufacturing process in South Africa. However, data on the quantities and composition of solid waste, liquid effluent and air emissions streams was not provided for life cycle inventory building purposes.

HFO production data used in the building of life cycle data modules was integrated into the data inventories for the used oil management options from TEAM™ 3 software's data modules on HFO. Information on the data modules from the software suppliers is provided in Appendix D.

This data, although based on European HFO production operations, was adjusted to reflect the process energy and material commitments calculated from the data collected for South African HFO production. For this reason, the data will be assumed be representative of South African HFO production scenario. The data was also adjusted to include South African Electricity production modules.

Data collected from the combustion of heavy fuel oils in industrial furnaces was collected separately for the individual industrial application and will be discussed in section 5.7 of the report.

5.5 RECYCLE AND WASTE MANAGEMENT: BURNING FOR ENERGY RECOVERY WITHOUT PRIOR TREATMENT, THE CEMENT KILN SOLUTION

Cement and Lime kilns were identified, in Chapter 2, as environmentally safe disposal facilities for used lubricating oils generated in South Africa provided emission control measures are implemented. (Mozes, 1997) Trials in which used oil was used as a substitute or complementary fuel for coal in the PPC Lime kiln incineration process were carried out in November 1995. The results of the trials, were not released for life cycle inventory building purposes but can be concluded to have been successful, as PPC Lime currently burns untreated used lubricating oil as a complementary fuel in its kiln incineration processes. (Norton, 1999)

Since the results of the study done in South Africa on burning used lubricating oils in high temperature kilns (Mozes, 1997) have not been released by proprietors for purposes of building life cycle inventories that formed the basis for comparative assessments in the research, experimental results from burning used oil in cement kilns, in other countries were used.

A life cycle inventory database was therefore built based on detailed work done by Berry et al (1975), in a report entitled, "Experimental Burning of Waste Oil as a Fuel in Cement Manufacture". It was assumed that the results of this work, in which used lubricating oils were burned in a carefully controlled experimental trial as a partial fuel in the St. Lawrence Cement Co.'s dry-process cement kiln at Mississauga, Ontario will form a comparable basis for the burning of used lubricating oils in high temperature kilns in South Africa, provided the operating and pollution control conditions are comparable.

5.5.1 The St. Lawrence Cement Company-Dry Process System

At the time of the experimental work the St. Lawrence Cement Company, Clarkson plant had a nominal production capacity of about 1 600 000 metric tonnes per year. The company operated two wet process kilns and one dry process kiln. The experimental trials were carried out in the dry process system which was separate from the other streams up to the point of clinker storage and grinding.

The dry process system consisted of a kiln, a suspension preheater, the alkali by-pass system and a dust precipitator. The Kiln was a 17' x 276' Taylor unit usually fired with No. 6 fuel oil. The suspension preheater is a unit specific to dry process manufacturing which consists of a system of cyclones and connecting pipes, through which the hot exit gases from the kiln are drawn by a fan. The preheater acts as a multi-staged heat exchanging system between the hot gases and raw meal feed, such that the raw meal enters the kiln at an approximate temperature of 800°C. The alkali bypass system is a system used to reduce the build up of chlorides and alkalies by by-passing a fraction of the kiln exhaust gasses through a conditioning tower. In the conditioning tower, water is sprayed into the gas stream to lower the temperature and condition the gases for precipitation. Concurrently the gas velocity is reduced since the cross section of the tower is greater than that of the by-pass product. The net effect of cooling and velocity reduction is to divide the particulate matter carried in the gas fraction into two fractions. A high alkali fraction (termed by-pass dust) becomes concentrated in a material stream which is ultimately collected in an electrostatic precipitator, pelletised and discarded. A fraction of the lower alkali content (termed conditioning tower solids) is returned to the raw feed silos and ultimately recycled into the raw feed stream.

The experimental work for this study was designed to examine the interaction between major waste oil contaminants and the total production system. The work was carried out to test the hypothesis that waste oil could be burned in a cement kiln without the adverse air impacts concomitant with burning it in conventional boilers or incinerators which do not have extensive facilities to cope with both normal and soot-blowing emissions.

The approach taken was to monitor normal plant kiln emissions before, during and after a period of used lubricating oil burning to determine experimentally the effect of waste oil burning on air quality. In addition a mass balance on the elements lead, bromine, zinc and phosphorous was carried out to determine where each element was collected in the process materials and the approximate extent of retention. Those elements already present in large quantities in cement manufacture (i.e. Ca, Si, Al, Fe and S) were omitted in the analysis as well as those elements reported in used lubricating oils with minimum contamination concentrations less than 100 ppm. Bromine was included in the study as its presence in the oil was expected from the composition of organo-lead anti-knock additives used in automotive gasolines, which contain ethylene dichloride and ethylene dibromide. No attempt was made to obtain a balance on chlorine due to the relatively large concentrations of this element in cement materials.

The different phases of the experimental work were carried out between 9 March and 30 May, 1974, with a total of 1.25 million litres of used lubricating oils burned.

Three sets of data were generated from the testing program. The first presented a baseline prior to burning used lubricating oil, under normal plant operating conditions. The second was taken at intervals throughout the waste oil burning period. The third was taken some time after waste oil burning had ceased.

From the analysis of the test results in the three testing periods the following observations were made:

- Comparison of average particulate loading data showed that between the first series of test carried out and during used oil burning there was a total reduction in particulates emissions. Part of this improvement may have been due to additional water introduced with used oil. It has been shown that water can improve precipitator efficiency even at relatively high temperatures.

- No significant changes were noted in the measured average loadings or emission rates of Pb, Zn or P. However a small increase in the average emissions of Br did occur during used lubricating oil burning.

- Lead and bromine were found in increased concentrations in the particulate materials collected during used oil burning.

- On the average, emissions from the kiln were restricted to approximately 0.03 % of the lead and 0.7 % of the bromine introduced with the used lubricating oil.

- Results of the mass balance showed that 89 % of the total lead in the system, most of which originates from the used oil, is retained in the process solids; from 75 to 85 % in the clinker and 9 % in the conditioning tower solids. The by-pass dust, the only material discarded (in pelletised form), was found to retain about 4 % of the total lead. The finding that lead is largely concentrated in the clinker would suggest that lead injected with the fuel must either be oxidised or taken into solid solution in the clinker in the body of the kiln.

- Results of the mass balance also showed that phosphorous and zinc were completely contained by the system. The containment was almost entirely within the clinker with only very minor percentages reported in the conditioning tower solids and by-pass dusts. The behaviour of phosphorous and zinc on cement have been examined and at the concentrations introduced by the used oil, no adverse performance was expected.

- Results of the mass balance showed that greater than 70 % of the bromine was found in the process solids. The majority of the bromide was reported in the collected by-pass precipitator dust. Bromine, owing to its great similarity with chlorine, is expected to exhibit the same behaviour. Chlorine is used as an additive in cement in various forms to reduce alkalies in the clinker.

Based on the above stated observations and using process flow emissions data the cement kiln module can be presented in a simplified diagrammatic form in Fig 5.3. The data module constructed for the burning of used oil in a cement kiln is presented in Table 5.5. Also given in Table 5.5 is comparative information from the tests done burning HFO in the cement kiln.

5.5.2 Cement Quality Concerns

The cements containing used oil contaminants that were produced during the burn were examined and no conclusive correlation between the cement quality and the content of lead, bromine, phosphorous was found. In addition, for a substantial number of the contaminants in used lubricating oils, enough is known to state that most or all will remain within the insoluble structure of the hydrated compounds in concrete.

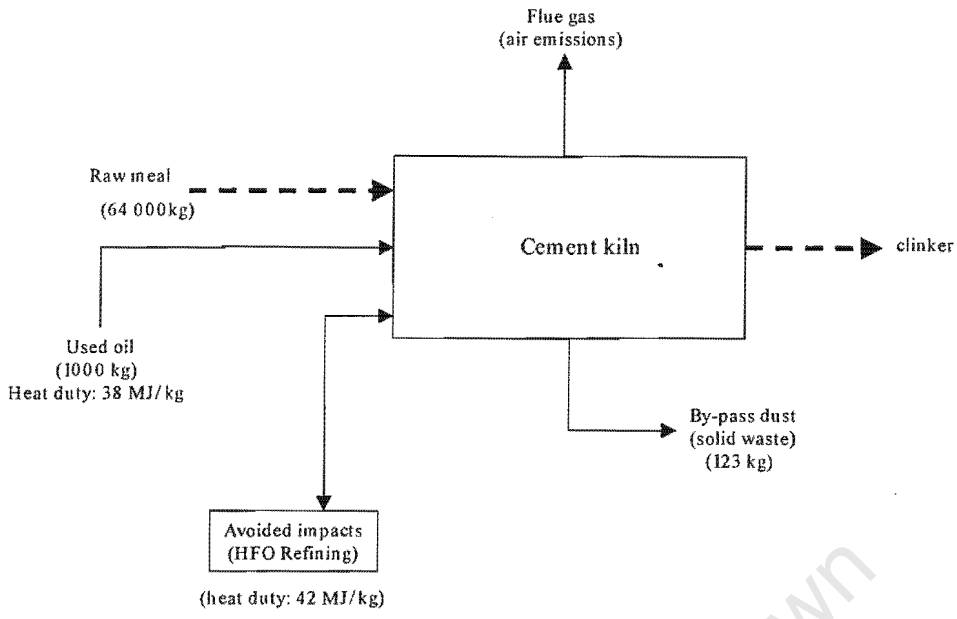


Figure 5.3 The main material, utility and environmental flows for the cement kiln

5.5.3 Extrapolation of Observation to Other Kiln Types

Due to the considerable variability of process types in the cement manufacturing industry, direct extrapolation of the observations of the results of the experiments to other types of kilns is difficult. However, some broad generalisations can be made considering the ways in which some elements are trapped in the kiln system. In summary the findings of the study would be applicable to kilns which have:

- Good scrubbing of the combustion gases with the solids in the kiln.
- Electrostatic precipitators or other suitable means of recovering the finest particulate matter.

As the precipitator efficiency decreases, this decrease would be greatest for the finest particulate matter, with which the contaminants of waste oil will be concentrated in open kilns. Thus it would imply that as the particulate emission increases, the emission of contaminants from the waste oil would increase at an even greater rate. From these observations it can be proposed that the disposal of used lubricating oils, as a fuel in cement kilns should be based on detailed experimental work done on each individual process to assess the extent of emissions as well as retention and resultant qualitative properties of the cement. The extent of emissions is directly related to the existence and efficiency of emission abatement equipment and these factors should be considered when implementing this used oil management option in South Africa.

Table 5.5 Data module for the burning of 1000 kg of untreated used oil in a cement kiln

material	units	Used oil	HFO
INPUTS			
Used oil	kg	1000	0
Raw meal	kg	64 000	64 000
HFO	kg	0	905
OUTPUTS			
clinker	kg	37 000	37000
WASTE STREAMS			
Flue gas	kg	20084	19806
(a) Barium	g	5	1
(a) Boron	g	1	1
(a) Calcium	g	--	--
(a) Chlorine	g	--	--
(a) Carbon monoxide	g	160	167
(a) Carbon dioxide	kg	2780	2978
(a) Chromium	g	2	1
(a) Lead	g	216	197
(a) Magnesium	g	2	2
(a) Nitrogen Oxides (NOx)	g	390	311
(a) Particulates	g	243	306
(a) Phosphorous	g	12	3
(a) Sulphur dioxide (SO_2)	kg	2.02	6.02
(a) Zinc	g	2	1
Solid waste	kg	123	123

"—" not measured

5.6 RECYCLE AND WASTE MANAGEMENT: REPROCESSING FOR SUBSEQUENT BURNING

Reprocessing equipment currently operational in South Africa is based on the use of a series of settling and centrifugation processes, finishing off the product by distillation using salvaged refinery equipment or using in-plant designed distillation/flash towers. The reprocessed product meets the particulates specifications as set for first world countries and has a relatively low sulphur content (McCabe and Newton, 1997). The reprocessed product is normally blended with heavy fuel oils to produce a product with a lower sulphur content as compared to the heavy fuel oils.

It was one of the aims of the research to produce a model forming the basis to compare the environmental performance of the locally designed reprocessing units as well as their product to patented units that are available internationally. Data modules generated from published operations data, for these internationally marketed reprocessing plants will therefore form a basis for comparison. However, accurate and consistently measured or documented process, utilities, effluents and emissions data for the local reprocessing operations was not available. For this reason data from the Revivoil Reprocessing Configuration was used in generating LCI data.

5.6.1 The Viscolube-IFP Revivoil Reprocessing Unit

Viscolube Italiana Spa, is a European used oil re-refining company which, with the technical co-operation of the Institut Francais du Petrole (IFP), developed the Revivoil series of used oil treatment processes. Viscolube-IFP has sold several, currently operational re-refining plants around the world, consisting of a combination of some or all of the following processing units: preflash, thermal deasphalting or vacuum distillation unit, propane deasphalting unit and a hydrofinishing unit. These plants have treatment capacities ranging between 30 000 and 100 000 tons of used lubricating oil per year but plants with a capacity as low as 10 000 tonnes/year can be built. The re-refining plants produce base oil product in accordance with international specifications, however one of the important features of the Revivoil Process is that, if required, a simplified version of the vacuum distillation unit without any second stage can produce a demetalized product suitable as an industrial or marine diesel fuel. (Giovanna et al, 1999; Billon et al, 1995; Viscolube Marketing Brochure, 1999)

The basic set up of the Revivoil reprocessing scheme will consist of the Preflash and the Thermal Deasphalting (TDA)/Vacuum Distillation Unit.

5.6.1.a Preflash

Used oil coming from the storage tanks is first filtered in a basket strainer before being pumped into a preheating stage. After preheating the used oil is sent to a mechanical mixer where the oil is blended with a pre-treatment additive. The oil and additive blend is subsequently passed through a heat exchanger system, which raises its temperature to 140°C to achieve the evaporation of water and light gasoil/solvents content.

The vapours coming from the preflash unit composed of water and light hydrocarbons are sent first to a condenser and cooled. Operating under a mild vacuum the residual water content is separated from the light gasoil. The water and light gas oil are stored and disposed of separately while the dehydrated oil from the bottom of the column is sent for further processing in the TDA. The light gasoil from the preflash may be used as fuel in the process.

5.6.1.b Thermal Deasphalting unit (TDA)

The dehydrated oil coming from the Preflash unit is sent to an intermediate tank where the oil interacts with the additive to separate materials in the used oil that can provoke fouling of the TDA furnace and distillation column. The precipitate from the additive use oil reaction is extracted from the bottom of the intermediate tank.

The intermediate tank product is sent to the process furnace where it is heated to a temperature of approximately 350°C. From the transfer line the charge arrives to the flash area of the column, where through a particular system, the asphaltic compound is separated by the vapours. The distillation column operates at a vacuum of about 0.02 atmospheres and has a high fractionating efficiency. The metal impurities and asphaltic substances present in the oil stay in the column bottom while reprocessed oil cuts are taken from the column. Gasoil is released at the column top and is sent to storage for use as fuel. The asphalt bottoms from the TDA process may be used as an asphalt extender, else they are disposed of as solid waste.

The process utility requirements for the Revivoil reprocessing configuration are given in Table 5.6. The configuration gives a yield of over 70% reprocessed oil, about 12 % asphalt and 6 % gasoil product. A typical composition of the reprocessed oil product from this operation is given in Table 5.7

Table 5.6 The process utility requirements for the Revivoil reprocessing configuration

Consumption& Utilities	unit	Preflash	Vacuum distillation
Electricity	kWh	1.5	12
MP steam	kg	285	322
Cooling water (make-up)	kg	1100	5000
Fuel (absorbed heat)	MJ	----	669.4

Source: Viscolube Brochure, 1999

- Consumption based on 100 000t/yr used oil capacity, considering 10% water contents
- All parameters are expressed in unit/ton of used oil feed

The burning of reprocessed oil in an industrial furnace was built into a unified data module incorporating the reprocessed oil production and burning in an industrial furnace. A configuration of this module is presented in Figure 5.4.

Table 5.7 Product composition from Revivoil used lubricating oil reprocessing configuration

Contaminant	
Ash (%)	0.02
Water (%)	<1
Vis @ 40oC (cSt)	104
Sulphur (% wt)	0.89
Conradson carbon (% wt)	0.01
Sediments (% wt)	----
	Averaged concentration (ppm)
Elements	
Aluminum	<1
Barium	<2
Boron	<2
Calcium	<2
Chromium	<1
Copper	<1
Iron	<1
Lead	3
Magnesium	<2
Molybdenum	<1
Phosphorous	125
Sodium	<1
Silicon	<1
Tin	8
Vanadium	<1
Zinc	<2

Source: Billon et al, 1995

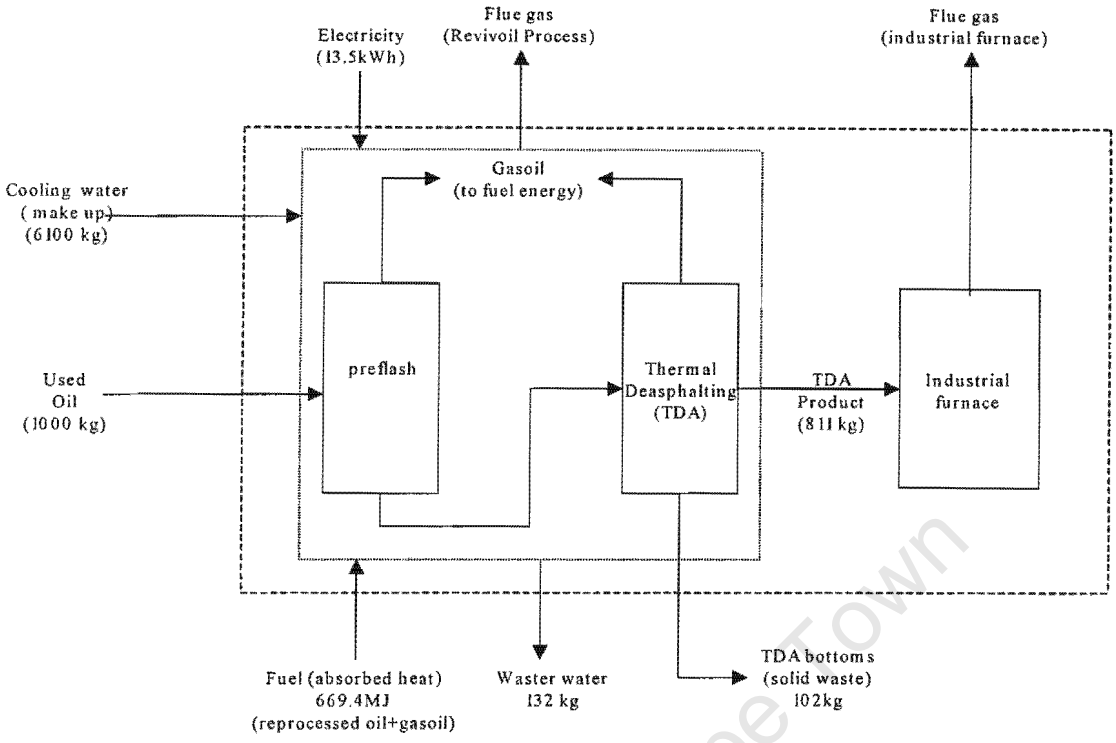


Figure 5.4 Combined module for the burning of reprocessed oil in an industrial furnace

5.7 RECYCLE AND WASTE MANAGEMENT: AN ASSESSMENT OF INDUSTRIAL PROCESSES BURNING REPROCESSED OILS

Reprocessed used lubricating oils are being burned in a wide variety of applications in South Africa. These include direct process firing furnaces, as a source of fuel for steam boiler furnaces and as a fuel in ceramics and brick manufacture. The furnaces in which the reprocessed fuel is burnt were typically designed for burning heavy fuel oils and no specific burner modifications are required, provided the viscosity of the blend is within the requirements of the burner.

A select number of furnaces that have had emission tests done for the burning of heavy fuel oil and reprocessed oil have been reviewed for purposes of generating life cycle inventory data. Analytical results for the burning of heavy fuel oil and reprocessed oil blends in the manufacture of bricks have also been used in the construction of another treated used oil burning life cycle inventory.

5.7.1 Burning Reprocessed Oil in an Industrial Furnace

The results of stack emissions measurement for the burning different types of oils, including a reprocessed oil, for energy utilisation in different industrial applications within the Sacks Circle industrial area in Cape Town were used to create the lifecycle inventory modules for burning reprocessed oils in industrial furnaces (Cairncross and Manuel, 2000). The furnace units in the Sacks Circle have oil burning capacities ranging between 80 litres/hr and 1200 litres/hr, stack heights range from 10m to 55m for the larger furnaces. However, no information was available to indicate the existence of any pollution abatement equipment on any of the furnace units. Detailed stack emission data was also obtained for the burning of heavy fuel oil at Shell and BP's blending plant, Blendcor's boilers. Stack emissions data from industrial operations in South

Africa were used to construct a data modules given in Table 5.7 based on a 1000 kg of used lubricating oil, reprocessed oil and HFO respectively.

Table 5.8 Data modules for the burning of untreated used oil, reprocessed oil and HFO respectively in industrial furnaces (data normalised to 1000 kg of oil)

parameter	unit	Used oil (untreated)	Reprocessed oil	HFO
Heating value	kJ/kg	38 000	42 000 (approx)	42 500
Sulphur	wt %	1.01	0.89	3.3
Ash	wt %	1.01	0.1	0.06
INPUT				
Used oil (untreated)	kg	1000	0	0
Reprocessed oil	kg	0	905	0
HFO	kg	0	0	894
Flue gas				
(a) NO	g	149	187	230
(a) NO_2	g	5.45	12.35	41
(a) SO_2	kg	17.1	13.93	48.91
(a) SO_3	kg	2.38	1.92	5.60
(a) Particulates	kg	5.51	1.91	1.02
(a) CO_2	kg	3197	2920	2787
(a) CO	kg	0.83	0.80	0.76
(a) As	g	1	1	--
(a) Ba	g	30	2	--
(a) Ca	g	1850	22	56
(a) Cr	g	7	1	--
(a) Cu	g	10	3	--
(a) Fe	g	1	5	--
(a) Mg	g	402	7	--
(a) Pb	g	1414	32	7
(a) P	g	642	117	--
(a) Zn	g	355	7	--

"—" not measured

Source: Cairncross and Manuel, 2000

5.7.2 Burning Reprocessed Oil in a Tunnel Kiln Brick Furnace

The burning of reprocessed oil in oil burning tunnel kiln furnaces has been considered as a viable waste management option in the used lubricating oil cycle because brick manufacturing processes are energy intensive processes and with spiralling energy and environmental costs it is in the interests of manufacturers to seek cheaper and cleaner fuels with equivalent energy content and similar burning properties. Reprocessed oils have been utilised as an energy source in South Africa as part of a blended oil product sold to the brick manufacturing industry. However, the stack emissions survey data, which is available for the burning of oils in brick making tunnel kilns, was generated with heavy fuel oil used as a fuel. These results have however been used to model the stack composition for a hypothetical burn of reprocessed oil. These model results, in

comparison with actual stack emission measurements have been used to construct life cycle inventory data modules.

The data used in the building of the brick firing inventory data module was obtained from a stack emission measurement undertaken at De Hoop Bricks, Paarl, from 3 to 4 May 1995 by C & M Consulting Engineers. The objective of the measurement program was to quantify the emissions from the brick-drying kiln under normal operating conditions, using heavy furnace oil (HFO), supplied by BP Southern Africa (Pty) Ltd. Sampling of volatile organic compounds (VOCs) and all chemical analyses associated with the VOCs and semi-VOCs were conducted by the Atomic Energy Corporation.

Available separately from De Hoop Bricks are stack emission results based on thermochemical calculations based on a computer program that calculates the equilibrium composition at specific conditions for reaction systems (in this case combustion) for the heavy fuel oil flow rate and approximate air flow rate. (Knotse, 1994)

The brick making process

The brick making process, which is illustrated by Figure 5.5 begins with the quarrying of suitable clay and its delivery into a preparation area. The preparation of clay involves clay milling and blending, which may include mixing with additives to yield a composition that produces the desired brick on firing. The blended clay product is mixed with a set ratio of water before entering the extruder which extrudes the green clay bricks in the required shape. The extruded product passes via conveyer belt through a well-timed green brick-cutting device, which cuts the bricks into their required size. From the extruder the bricks are stacked onto rail-mounted trolleys or cars which hold over 2000 bricks a trolley depending on packing order and brick sizing.

The brick loaded trolleys pass through a drying zone, with each trolley having an average residence time of 36 hours. The drying zone has a temperature profile ranging between 50 and 250°C within the length of the drying zone. The drying zone is heated from exhaust gases exiting the firing zone of the tunnel kiln furnace and are driven by air force-feed fans.

The kiln is a continuous tunnel unit which carries brick trolleys with a residence time of between 21 and 24 hours. The De Hoop tunnel kiln firing zone is fired from burners located at the roof of the furnace. Fuel oil enters the burner system, which consists of a series of pulsating firing burners followed by air atomised continuous firing burners. Air enters the kiln under the driving force of the exhaust fan and it is sucked counter current to the flow of the trolleys. The airflow through the kiln is monitored and regulated to maintain the required temperature profile. The temperature in the kiln rises steadily from about 50°C at the entrance to the drying zone to about 1080°C in the firing zone. An air compressor supplies compressed air to the injection nozzles which is used to atomise the oil, whilst providing the required oxygen for combustion.

Internal circulation of hot air is employed to maximise energy efficiency and the air's energy content is also exhausted in the drying zone before it leaves the system through the stack.

About 7000 litres of fuel oil, with an average sulphur content of 3.3 % are burnt per day. However, a mass balance carried out based on the SO_2 going out the stack showed that 56 % of the sulphur introduced with the heavy fuel oil was emitted out of the stack, with the remainder being retained within the furnace system.

A number of explanations have been suggested for the observed sulphur retention in the brick making system. Scanning electron microscopy tests showed that sulphur bearing particles were present on air filters but could not be quantified with any degree of accuracy. A laboratory analysis of stack residue showed that the residue contains about 20 % sulphur (BP Lab Report,

1984). It is also believed that a large proportion of the sulphur retained is adsorbed as sulphur oxides onto the kiln wall and onto the green brick surface. Laboratory tests done on fired brick material showed that the brick contained up to 4 % sulphur (J Muller Laboratories Reports LN911457-D026-06, 1999; LN003319-D026-08, 2000; LN001097-D020-06, 2000). These results came from once off tests and more detailed analyses may be necessary to ascertain the mechanism by which sulphur oxides are retained in the tunnel kiln.

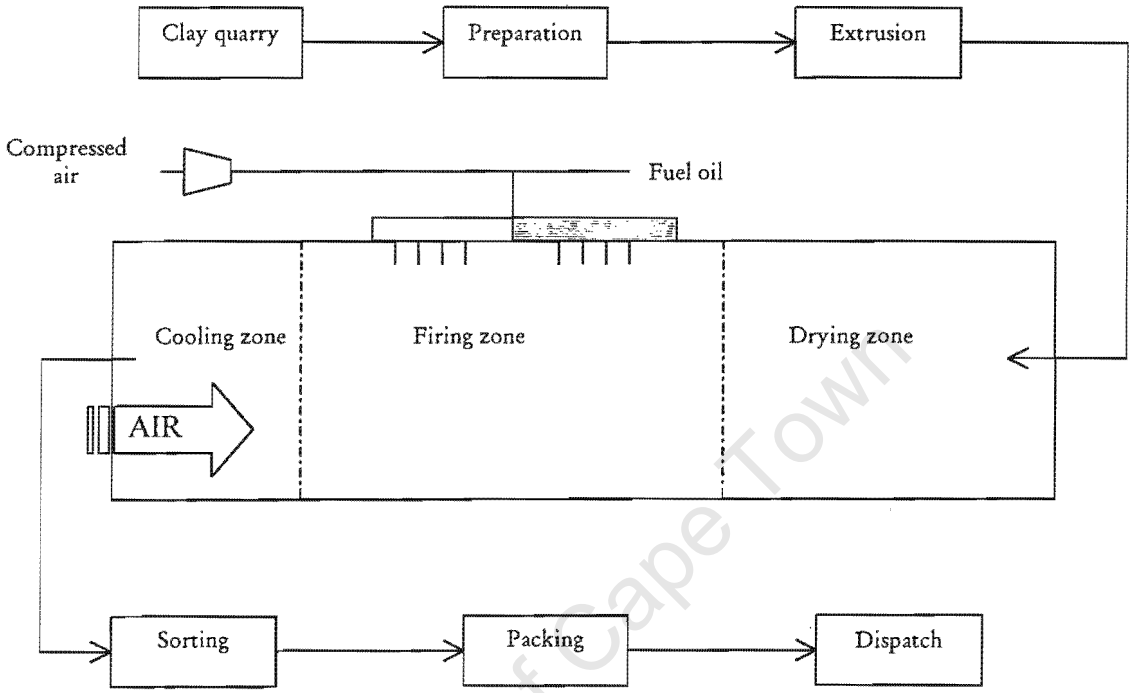


Figure 5.5 The brick making process at De Hoop Bricks, Paarl

Based on the above noted interactions of sulphur products in the kiln, the assessment of the thermochemical model by Knotse (1994) and stack emission data from tests carried out by C & M Consulting Engineers a module representing the burning of reprocessed oil in a brick kiln was built. Table 5.9 gives the data module for the burning of reprocessed oil based on 1000 kg of oil.

Table 5.9 Data module for the burning of reprocessed oil in a brick kiln (data normalised to 1000 kg of oil)

parameter	unit	Reprocessed oil	HFO
Heating value	kJ/kg	42 000 (approx)	42 500
Sulphur	wt %	0.89	3.3
Ash	wt %	0.1	0.05
INPUT			
Used oil (untreated)	kg	0	0
Reprocessed oil	kg	1000	0
HFO	kg	0	988
Flue gas			
(a) NO	g	62	67
(a) NO_2	g	12	--
(a) SO_2	kg	8.08	32.23
(a) SO_3	kg	1.22	7.21
(a) Particulates	kg	1.91	1.03
(a) CO_2	kg	3227	3079
(a) CO	kg	0.80	0.76
(a) As	g	1	--
(a) Ba	g	2	--
(a) Ca	g	22	--
(a) Cr	g	1	--
(a) Cu	g	3	--
(a) Fe	g	5	--
(a) Mg	g	11	--
(a) Pb	g	38	--
(a) P	g	122	--
(a) Zn	g	10	--

"—" not measured

5.8 RE-REFINING TO PRODUCE LUBRICATING BASE OIL OF A QUALITY EQUIVALENT TO VIRGIN BASE OIL

There are many re-refining technologies that are available for consideration in treating used lubricating oils collected in South Africa. (See Tables 2.11.a and 2.11.b) However, the Revivoil process jointly developed by the Italian re-refining company Viscolube Italiana Spa and the French petrochemical company Institut Francais du Petrole (IFP) has been selected as the representative re-refining technology for purposes of building life cycle inventory data modules for the re-refining management option. The Revivoil re-refining process was selected as the representative re-refining technology for the following reasons:

- Viscolube is a company specialising in the development of re-refining technologies, and has the largest combined used oil processing capacity in Europe. Viscolube also has commissioned more than seven currently operational re-refining plants around the world with capacities ranging from 30 000 to 100 000 tonne/year capacity plants.

- Institut Francais du Petrole (IFP) is also engaged in designing petrochemical and refining technology with over 1200 quoted industrial references. IFP has a large research and development department equipped with pilot plants where products can be treated and thoroughly tested until process specifications are defined and plant configuration is designed with far greater guarantee of performance than theoretical design carried out by an engineering company. IFP is also involved in the development of hydrotreating processes.

- The Revivoil process accepts all mineral oil feedstocks and produces high yields of high quality base oils. A number of European motor manufacturers have approved the use of Viscolube's 150N re-refined oil and it is blended with Lubrizol additives 4980N and 7077 for use in turbo charged heavy-duty diesel engines.

- In advertising their process Revivoil makes available detailed information on their process utility requirements and detailed analytical results from tests carried out on their product and waste streams, thus allowing the LCA researcher to build a robust and realistic life cycle inventory module for the re-refining option for used lubricating oil management. Process and utility information for the Revivoil process was obtained from a paper presented by Giovanna et al at the Used Oil Management Conference in 1999 as well as the Revivoil technical brochure published in 1999. Chemical analysis results on the products and waste streams were obtained from a paper presented by Billon et al in 1995.

The Revivoil process is available in two configurations as shown in Figures 5.6 and 5.7 respectively. In the first configuration used oil is taken through the following treatment processes: preflash, thermal deasphalting and hydrofishing, giving an average product yield of 73 % based on the used oil feed. In the second configuration the Revivoil process has all the above named treatment stages, but includes a solvent treating stage for the thermal deasphalting bottoms product which is sent through to hydrofinishing thus giving a higher base oil yield of about 80 % on the used oil feed. Each of the treatment stages of the Revivoil process will be described in greater detail and the analytical results of the products streams from the two configurations will be given.

Data modules were built for both lower base oil yield thermal deasphalting-hydrofinishing process and the higher yield configuration with the propane-deasphalting unit. A simplified diagrammatic representation of the data module for the high yield Revivoil configuration is given in Figure 5.8.

5.8.a Preflash

The preflash is as described before in Section 5.6.1.a for the Viscolube-IFP Revivoil Reprocessing unit.

5.8.b Thermal Deasphalting unit (TDA)

The Thermal Deasphalting unit is as described before in Section 5.6.1.b for the Viscolube-IFP Revivoil Reprocessing unit.

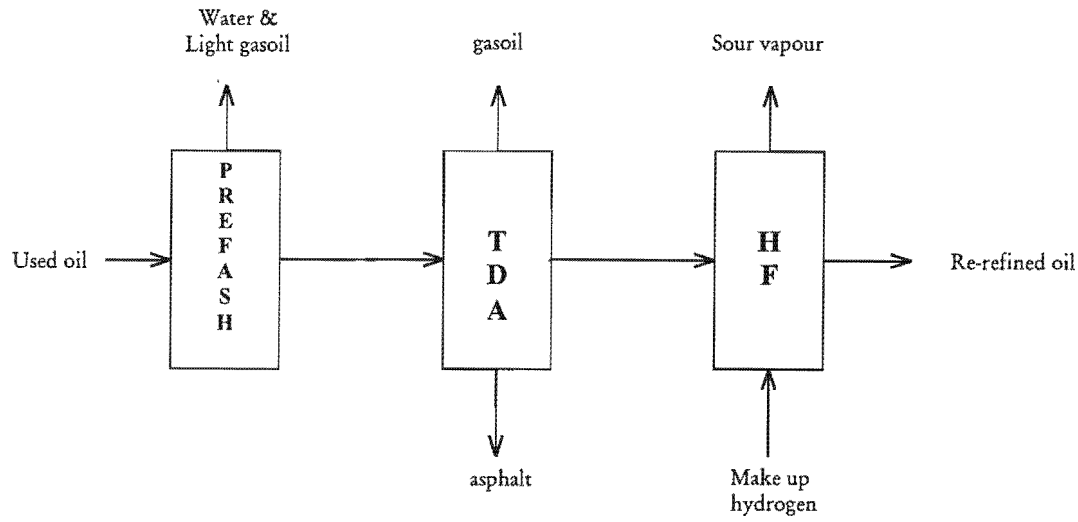


Figure 5.6 The Revivoil Re-refining scheme without heavy oil recovery

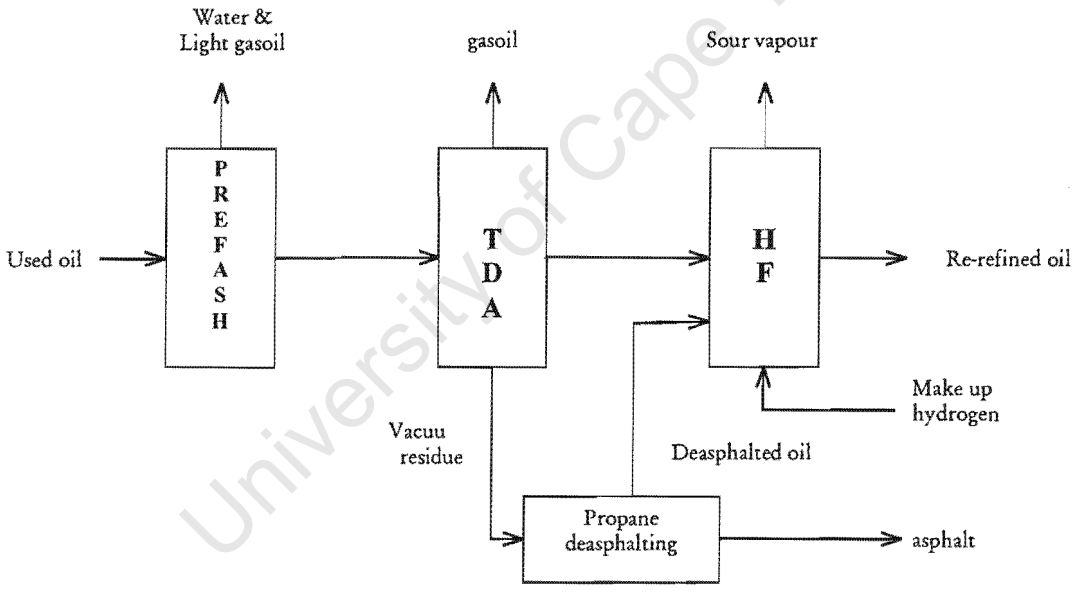


Figure 5.7 The Revivoil Re-refining scheme with heavy oil recovery

5.8.c Hydrofinishing (HF)

The intermediate products coming from the thermal deasphalting unit (TDA) are bleached with a catalyst system. The catalyst system consists of the demetallisation catalyst and the refining catalyst. The purpose of the demetallisation catalyst is to remove the remaining metals from the intermediate feed. The catalyst, which was designed by IFP has a considerably greater retention time than the refining catalyst and has a large pore volume and pore distribution. It allows deposit of metals throughout the particle, and a high metal retention of up to 60 to 80 % of the weight of catalyst. The refining catalyst has the main purpose of finishing the already transformed feed. It removes the remaining Conradson carbon, organic acids and compounds containing

chlorine sulphur and nitrogen. Colour, UV and thermal stability are restored, the polynuclear aromatics are reduced to values far below health thresholds while the viscosity index remains equal to or better than the original feed. The sour vapour from the hydrotreating process is taken for further processing to process the stripped hydrogen sulphides before being recycled as make-up fuel gas to the furnace system.

5.8.d Propane Deasphalting (PDA)

The propane deasphalting process is an optional treatment stage used to increase the overall yield of the re-refined oil product. Residue from the thermal deasphalting column is contacted with propane in an extractor. In the extractor column the bottoms-propane mixture separates into two phases:

The heavy phase at the extractor bottom is a mixture of ultimate residue and propane. This phase is drawn off from the extraction unit and is taken through a stripping stage where the propane is recovered and the asphaltic residue product is sent to storage.

The light phase at the top of the extractor is a mixture of recovered oil and propane. The oil-propane mixture is taken through a mild vacuum high temperature stripping stage from which the propane is recovered and the deasphalted oil product is sent for further treatment in the hydrofinishing unit.

5.8.1 Consumption and Utility Requirements for the Revivoil Process

The process consumption and utility requirements for the two Revivoil process configurations are given in Table 5.10.

The Revivoil process produces a number of distillate cuts which are put through the hydrofinishing process. Presented in Appendix C are the analytical results on some of the process streams. Results were obtained from the LPC Hellas plant in Greece, operational since 1993.

Table 5.10 The process consumption and utility requirements for the different configurations of Revivoil re-re-refining processes

Consumption & Utilities	unit	PF	TDA	HF	PDA
Traditional TDA System					
Electrical consumption	kWh	1.5	12	20	----
MP steam	kg	285	322	70	----
*Cooling water (make up)	kg	1100	5000	300	----
Fuel (absorbed heat)	MJ	----	669.4	711.3	----
Hydrogen	kg	----	----	2.1	----
**Catalysts	kg	----	----	200+50	----
Propane make up	kg	----	----	----	----
High Recovery System					
Electrical consumption	kWh	1.5	12	20	13
MP steam	kg	285	322	70	135
*Cooling water (make up)	kg	1100	5000	300	4000
Fuel (absorbed heat)	MJ	----	669.4	711.3	920.5
Hydrogen	kg	----	----	2.1	----
**Catalysts	kg	----	----	200+50	----
Propane make up	kg	----	----	----	0.93

* based on 10% evaporation losses
** Demetalisation catalyst + refining catalyst

Source: Viscolube Brochure, 1999

- Consumption based on 100 000t/yr used oil capacity, considering 10% water contents
- All parameters are expressed in unit/ton of used oil feed

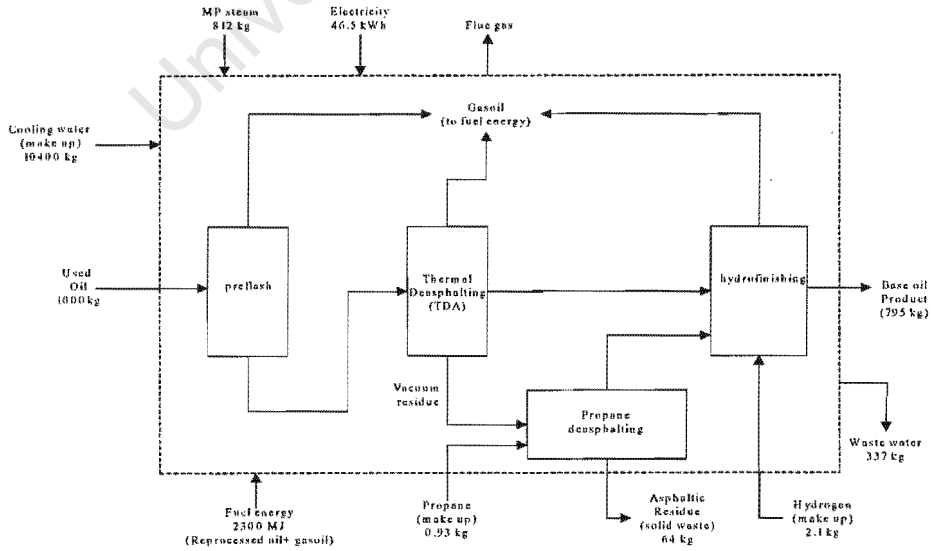


Figure 5.8 Model of data module for the high yield, propane deasphalting Revivoil configuration

5.9 CONCLUSIONS

This chapter has presented the processes, unit processes and recycling options constituting the life cycles of the selected used oil management options in South Africa. The data gathering process was also reviewed and it can be concluded that there generally is a lack of process data that is of a quality to enable the construction of complete life cycle inventory data modules (i.e. the quantities and compositions of process streams, utilities, effluents, solid wastes and emissions are not fully defined). The process of building data modules for local used oil recycling processes will require significant financial and labour inputs, and it was not considered feasible within the scope of the study to carry out these detailed analyses. However missing data categories have been identified, thus forming a basis for recommending future data collection efforts. The selected data modules for the re-refining and reprocessing of used oil, as well as the burning of used oil in cement kilns is represented by process data documented for operations in other countries. There is scope for gathering data on the local recycling options for used oil management for the purpose of comparing their environmental performance to patented units being marketed internationally and thus using the results of this research as a benchmark for improving local used oil treatment processes.

Data modules that were needed for the comparative analysis of used oil management options were also presented in this chapter. These data sets were incorporated into an LCA based computational model that was built to compare the environmental performance of selected used oil management scenarios in South Africa. The computational model is described in Chapter 6.

Chapter 6

Building of the Life Cycle Inventories

6.1 INTRODUCTION

The purpose of this chapter is to describe the LCA based computer model that was constructed and used to generate inventory results for a selected number of used oil management scenarios. The results generated will be interpreted in Chapter 7 and assessed in Chapter 8 using life cycle impact categories available in the TEAM™ 3 LCA computational software.

The chapter begins by reviewing TEAM™ 3 by Ecobilan. The software's operating philosophy and its databases are discussed and the procedure for carrying out an LCA project within TEAM™ 3 is also described.

Following the review of TEAM™ 3 LCA software the computational model that was constructed for carrying out the comparative environmental life cycle assessment of selected used oil management scenarios in South Africa is described. The computational model was used to generate aggregated inventory results that will form the basis for interpretation and impact assessment. The data modules used in building the computational model are presented and the calculation process used by the TEAM™ 3 software to aggregate the inventory flows is described.

6.2 DESCRIPTION OF THE TEAM™ 3 SOFTWARE FOR ENVIRONMENTAL LIFE CYCLE ANALYSIS

TEAM™ 3 is a computational software tool for evaluating life cycle environmental and cost profiles of products processes or activities. TEAM, the acronym, stands for Tools for Environmental Analysis and Management. TEAM™ 3 is the most recent version of the Ecobilan Group's LCA software and it allows the user to build and use a large database and to model any system representing the operations associated with products, processes and activities (waste management options, means of transportation etc.).

TEAM™ 3 is designed to describe complex industrial systems and to calculate the associated: (The Ecobilan Group, 1999)

- Life Cycle Inventories (LCI)
- Life cycle potential environmental impacts
- Process oriented life cycle costs.

In the research presented here the cost profiles for the used oil management options were not considered and TEAM™ 3 was used specifically for environmental life cycle analysis.

The TEAM™ 3 package also includes two databases (TEAM™ User's Manual, 1999):

- The DEAM (Data for Environmental Analysis and Management) starter kit that includes data sets, defined as data modules in TEAM™ that cover the most common industrial sectors or activities encountered while performing a Life Cycle Inventory Analysis. Various versions of the starter kit exist, which reflect different regional conditions. The DEAM™ 3 starter kit provided with the TEAM™ Software for the research contains over 600 data

modules mainly from European industrial operations but also includes data modules specific to South Africa such as "Electricity Production: South Africa, 1996"

- The DEAM™ Methods, which includes Life Cycle Impact Assessment (LCIA) and Valuation methods.

Each database in the DEAM™ starter kit is made of data sets generally representing process steps, containing quantified input and output data values. The actual input and output flows in the data sets are distinguished using either a prefix, a name, a suffix and additional information (in parentheses). Of importance to presenting tabulated inventory results are the distinguishing prefixes which indicate the fate of the inventory flow. The distinguishing prefixes, names and other aspects are presented in Table 6.1.

Table 6.1 Description of distinguishing prefixes for the TEAM™ 3 inventory flow data

prefix	example	description
(r)	(r) Coal (in ground)	Flows represent non-extracted natural resources (generally in ground) (units: kg)
(a)	(a) Carbon Monoxide (CO)	Flows represent air emissions (units: grams (g))
(w)	(w) Lead (Pb++, Pb4+)	Flows represent water effluents (units: g)
(s)	(s) Ultimate Waste	Flows represent elementary flows released to land (units: kg)
(ar)	(ar) Uranium (U238)	Flows represent radioactive air emissions (units: kBq)
(wr)	(wr) Lead (Pb210)	Flows represent radioactive water emissions (units: kBq)
E	E Feedstock Energy	Flows represent energy reminders (units: MJ)

Source: DEAM™ User's Manual, 1999

Data sets are either included in the TEAM™ 3 software as a TEAM™ Module (input/output list) or as a TEAM™ System (description of an industrial system). Modules are viewed through a spreadsheet like interface and systems are viewed using one of two available interfaces: classical, or graphical. Some of the different industry sectors covered in the DEAM™ Starter Kit are:

- Energy production
- Transport
- Chemicals Production
- End of Life
- Plastic production and conversion
- Glass
- Steel
- Aluminium
- Metals
- Pulp and paper

The biographical Data sets of the starter kit were taken out of four principal sources:

- BUWAL 250 for package 'steel', 'aluminium', and 'pulp and paper'
- ETH for package 'energy', 'transport', 'metals' and 'end of life'
- APME for package 'plastics production and conversion'
- BUWAL 250 and 232, ETH and <Chauvel.A> for package 'chemicals'

6.3 DESCRIPTION OF THE COMPUTATIONAL MODEL

One of the specified objectives of the research was to develop a technique whereby an LCA based model could be used to investigate and evaluate the environmental performance of specific scenarios for used lubricating oil management in South Africa and thereby form a basis for recommending improvements. A computational model was constructed using TEAM™ 3 environmental Life Cycle Analysis software that incorporated the selected used oil management options into a single life-cycle process tree. The computational model was used in the research as a tool for the comparative assessment of the environmental performance of the selected, hypothetical used oil management scenarios wherein the entire volume of used oil collected in South Africa is utilised through each of the selected used oil management options presented in Chapter 4 of the thesis on Goal and Scope definition. A simplified diagrammatic representation of the developed computational model is presented in Figure 6.1.

The simplified diagrammatic representation of the computational model consists of data modules constructed into interlinked system sub-levels and sub-sub-levels connected and calculated to form the main system. The modules that constitute the systems, sub-systems and sub-sub-systems for the computational model are presented in Table 6.2. Information on the sources, comments and applicability of the data for all the data modules used in constructing the computational model is given in Appendix D in the thesis.

The working of the computational model will be described using Figure 6.1

A, B, C represent the flow of crude oil, lubricating base oil and blended oil, respectively (in kilograms) from extraction, refining and blending of crude oil. D, E, F represent the flow of collected used oil through to disposal via any one of the selected used oil management options. R represents the mass flow of re-refined oil being recycled back into blending operations within the used lubricating oil re-refining option life cycle. These flows are normalised to a functional flow of 1000kg of collected used oil in the analysis.

Assuming the re-refining option has been selected within a used oil management scenario then;

$$B = C - R \text{ - Additives} \quad (1)$$

TEAM™ 3 recognises the creation of a recycle stream and will automatically adjust the flows A and B and their associated sub-modules and sub-sub modules flows based on the new value of B.

The analysis of base oil refining process units associated with the production of base oils in South Africa, presented in section 5.2.5 showed that the volume of crude oil processed in the upstream fuels refinery units would be independent of the reduction in processing capacity in the base oil refinery. For this reason, the results of the comparative analysis of used oil management scenarios will be independent of environmental burdens associated with crude oil extraction. Hence stream A, is defined to represent that quantity of crude oil from the fuels refinery into the base oil refinery coming in as vacuum product for further processing.

a, b, c, d, e represent the fractions of the total volume of collected used oil that are distributed to the respective used oil management options. These fractions are defined in the computational model at the node where stream F splits into the selected used oil management options.

$$a + b + c + d + e = 1 \quad (2)$$

Based on the proposed functional flow of 1000kg of collected used oil,

$$aE + bE + cE + dE + eE = 1000kg \quad (3)$$

For example, if it is assumed that for a given used oil management scenario for used lubricating oils in South Africa 50 % of the total volume of collected used oils is re-refined, 20 % is burned in cement kilns and 30 % is reprocessed for subsequent burning then;

$$a = 0.5, b = 0.3, c = 0, d = 0 \text{ and } e = 0.2$$

The values of A, B, C, D, E and R are determined from the calculation processes in the TEAM™ 3 computational software. The value of E, which represents the functional flow of collected, used oil is specified in a propagation tool in the TEAM™ 3 software. All other flows are normalised to the functional quantity of collected used oil that is specified.

Critical to the specification of a used oil management scenario are the values assigned to the fractions of total used oil volume distributed to a particular use by specifying the values of **a, b, c, d** and **e.**

After the values of **a, b, c, d** and **e** are assigned for a given functional flow value the inventory results for a used oil management scenario are calculated. Snapshots of the generated inventory results are transferable to TEAM™ 3 software's interpretation tool from which the individual and comparative analyses of inventory results of different used oil management scenarios can be compared. The interpretation tool may also be used to assess the inventory results of each individual used oil management scenario. For example, the interpretation tool can be used to quantify separately, for a selected inventory flow, the contributions of the sub-systems and sub-sub-systems.

The inventory results generated in the TEAM™ 3's system editor and transferred to the interpretation analysis tool can be analysed based on material flows, selected environmental stressors as well as using Life Cycle Impact Assessment methods. The results of the interpretation analysis can be presented using tabulated inventories or using charting methods from TEAM™ Explorer in the interpretation analysis window.

As an example the model may be used to investigate Hypothesis 2 for the thesis, which states that:

Of the stated methods of used oil management, and working on the basis of applying the best available technologies for each management option, re-refining is the most environmentally sound solution for the management of used lubricating oils generated in South Africa.

The above stated hypothesis seeks to compare environmental performance of the selected used oil management options. In the computational model the selected models will be compared based on the assumption that there exists a used management scenario in which all the collected used oil is distributed to and disposed through one selected used oil management option. These mono-disposal route management scenarios are specified in the computational model by generating inventories based on specifying the value of the fraction of the collected used oil volume (a, b, c, d or e) to equal 1 (one) while all the other values are equal to zero. For example, if it is assumed that the entire volume of collected used oil is recycled then;

$$a = 1, b = 0, c = 0, d = 0 \text{ and } e = 0$$

Inventories for the five selected used oil management options to be compared in verifying Hypothesis 2 were generated from the computational model using the above described method in the interpretation analysis tool in the TEAM™ 3 software.

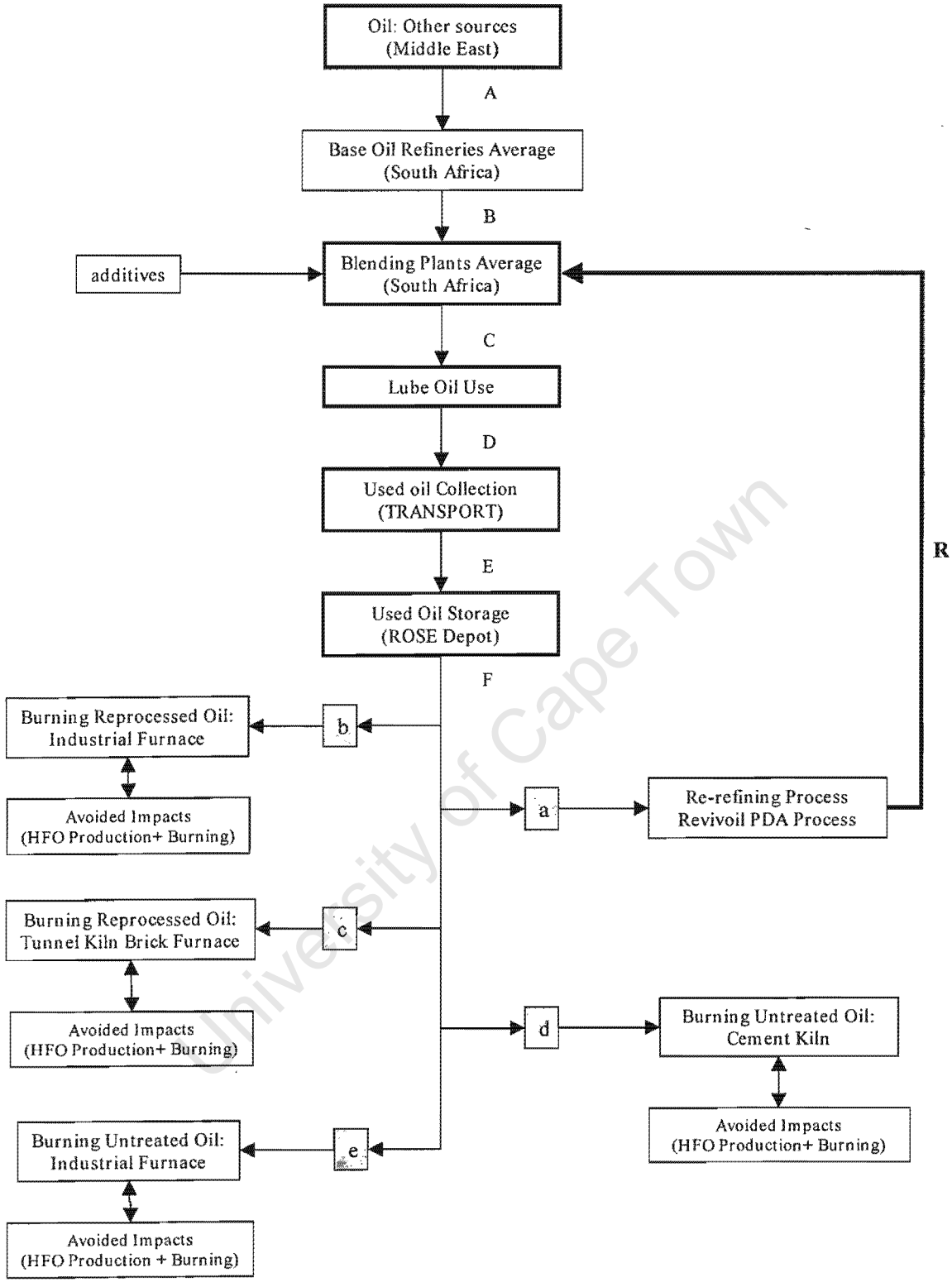


Figure 6.1 Simplified diagrammatic representation TEAM™ 3 based computational model for the comparative analysis of the environmental performance of selected used oil management scenarios in South Africa

Table 6.2 List of modules, sub-modules and sub-sub-modules constituting the computational model for the assessment of used oil management scenarios in South Africa

Module	Sub-module	Sub-sub-module
Refineries average (South Africa)	• 401 Electricity (South Africa, 1996): Production.1 • 402 Liquid Petroleum Gas (LPG): Combustion (2).1 • 403 Steam: Production in Refineries.1 • 2321 Naphtha: Refining.1 • 2321 Propane (C3H8): Production.2 • 241 Toluene (C6H5CH3): Production.1 • 4031 Heavy Fuel Oil: Combustion (Refinery).1	

6.3.1 Aggregation of Data by TEAM™ 3 LCA Computational Software

The comparative analysis of the used oil management scenarios will be based on aggregated inventory results generated for the life cycle systems under consideration.

Inventory results are presented in TEAM™ 3 as input or output main (closed loop) flows, emissions to air, contaminants in water, contaminants to land and utility requirements. TEAM™ can present over 600 different flows in its inventory based on the system constitution. Each of these aggregated inventory flows given for the main system is constituted of the contributing quantities of that flow from the sub-systems and sub-sub-systems. All avoided impact flows are subtracted from the aggregated inventory value in the system life cycle inventory results.

The aggregation process of inventory flows is illustrated in Table 6.3 based on 10 selected inventory flows for the sub-system generated to represent the South African lube base oil refinery operations. The sub-system representing the refinery operation which is named Refineries Average in the computational model is presented with its associated sub-sub-system modules in Figure 6.2. The individual mass contributions of a selected flow to the aggregated sub-system inventory flow are compared using a bar graph presentation in Figure 6.3 The results presented in Figure 6.3 are based on comparing the individual sub-sub-system total used water contributions to the aggregated inventory's total used water quantity. Such analyses and comparisons as indicated in Figure 6.3 serve to identify the areas in a given life cycle making significant contributions to a flow and hence assisting in identifying areas of improvement.

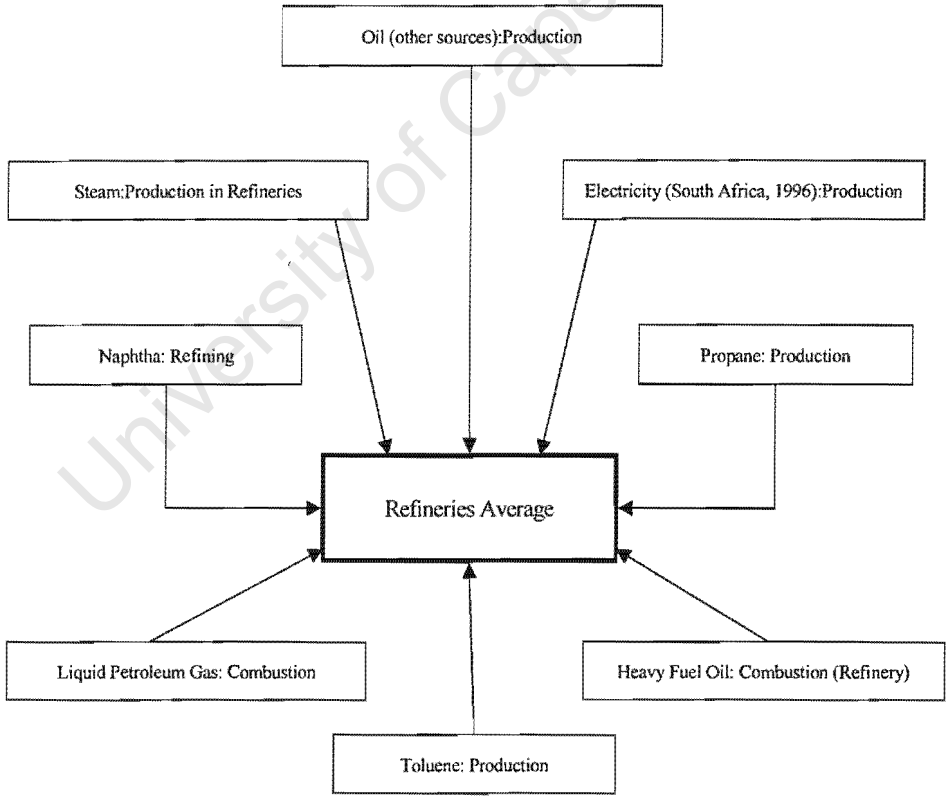


Figure 6.2 The refineries average sub-system and its associated sub-sub-systems

Table 6.3 Illustration of the aggregation process of inventory folws as calculated in the TEAM 3 software based on 10 selected inventory flows of the refinery sub-system presented in Figure 6.2

	Flow	Units	INVENTORY	Oil: other sources	Naphtha: Refining	Propane: Prod	Toluene: Prod	Electricity : Prod	LPG: Combustion	Steam: Production	HFO: Combustion	refineries average
Inputs:	(r) Oil (in ground)	kg	13395	13261.90	99.27	0.64	0.40	0	23.09	5.86	3.78	0
	E Fuel Energy	MJ	933.46	0	0	0	0	0	0	0	0	933.46
	Electricity	MJ elec	24.19	0	23.34	0.20	0	0	0	0	0.65	5.92
	Water Used (total)	litre	1074.11	431.51	407.54	2.66	1.34	1.96	0	68.44	15.52	145.16
Outputs:	(a) Carbon Monoxide (CO)	g	995.17	915.32	17.36	0.15	0.36	1.96	46.73	12.67	0.61	0
	(a) Nitrogen Oxides (NOx as NO2)	g	29392.80	28767.10	105.62	0.54	4.13	3.51	111.32	380.20	20.37	0
	(a) Sulphur Oxides (SOx as SO2)	g	12658.20	11768.40	285.72	1.91	1.82	7.78	77.36	354.85	160.38	0
	(w) Water (unspecified)	litre	64.14	0	0.02	1E-05	0	0.90	0	0	0	63.22
	(w) Water: Chemically Polluted	litre	418.59	0	403.09	0.14	0	0.01	0	0	15.35	0
	Waste (total)	kg	20.58	19.35	0.43	0	0.01	0.51	0	0.26	0.02	0

Note: Inventory results presented in Table 6.3 are inaccurate and have been presented for the purpose onf illustrating the inventory calculation process only.

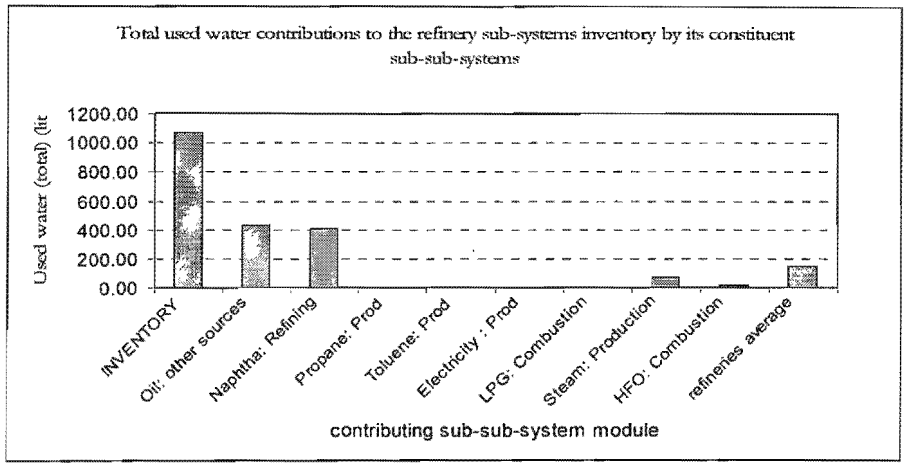


Figure 6.3 Total used water contributions by the refinery sub-system by its constituent sub-sub-system inventories

6.4 CONCLUSION

In this chapter the computational model that was constructed for the purpose of carrying out a comparative analysis of the environmental performance of selected used oil management scenarios was described and its working approach was illustrated using a simplified diagram. The results of the comparative analysis will be presented in Chapter 7, and in Chapter 8 on the basis of selected life cycle impact assessment categories.

Chapter 7

Interpretation of Life Cycle Inventory Results

7.1 INTRODUCTION

In this chapter the results generated from the computational model, described in Chapter 6, are presented and analysed. The results and their analysis will be based on a selected number of inventory flows.

The chapter begins by presenting and reviewing the inventory flows that were selected for analysis of inventory results. The results are then presented and analysed based on the inventory flows in tabulated and graphical formats. The analysis of results will be based on the quantitative comparisons of the selected inventory flows for the alternative used oil management scenarios and by assessing the contributions of the life cycle stages of the management scenarios.

The selected inventory results will be analysed with a focus on meeting the objectives of the research and verifying the proposed hypotheses that are presented in Chapter 1 of the thesis. Results of sensitivity analyses carried out on the assumption that has been made for allocating environmental burdens in the base oil refinery system will be presented. The inventory results of a few of the flows presented in this chapter will also be analysed in detail, identifying the areas contributing to quantitative differences for respective flows to each used oil management scenario.

The chapter is concluded by discussing the trends in environmental performance identified from analysing the inventory results for the selected used oil management scenarios, as well as presenting the conclusive deductions that may be made from the analyses.

7.2 PRESENTATION OF THE ENVIRONMENTAL STRESSORS USED IN THE ASSESSMENT

Team 3 LCA computational software can generate over 500 different flows in its inventory list for a given system, depending on the system's module constitution. In the assessment of the selected used oil management scenarios 292 inventory flows were generated by the software representing system life cycle flows. An inventory flow based comparative analysis of the selected used oil management scenarios cannot be based on all 292 inventory flows and a select number of flows which may be considered to be important environmental performance indicators in South Africa will be used. The inventory flows selected for the analysis are presented in Table 7.1. The inventory results of the comparative assessment are also presented using over 200 inventory flows in Appendix E.

Table 7.1 List of environmental stressors or inventory flows to be used in presenting and assessing the environmental performance of selected used oil management scenarios in South Africa

Resource use flows	Environmental burdens
Water (total water used)	SO_x (air emission)
Fuel Energy	Particulates (air emission)
Coal in Ground	Pb (air emission)
	NO_x (air emission)
	Unspecified oils (water pollutant)
	Chemically Polluted Waste Water (unspecified composition)

7.2.1 Reasons for Selecting the Inventory Flows Presented in Table 7.1

- South Africa has limited water resources and industrial systems or technologies that minimise water use and produce minimum quantities of polluted water are clearly more attractive. Based on this recognised need to minimise the consumption and pollution of scarce water resources in the country, the volume of waste water and the content of unspecified oils in water streams have also been selected as a basis for comparing the selected used oil management scenarios in the thesis.

- Fuel Energy is a term used in the TEAM™ 3 software to describe materials directly consumed in the provision of energy. Liquid petroleum gas (LPG), heavy fuel oil (HFO) as well as used oil used as a fuel are aggregated Fuel Energy flows that will form the basis for assessing the environmental performance of the selected used oil management scenarios. Fuel energy has been selected as a representative resource use flow because its constituent fuels are derived from crude oil, a valuable raw material input whose processing and ultimate consumption as oil based products releases significant quantities of wastes and emissions to the environment.

- Coal is considered to be an important resource use flow in South Africa as the electricity generated in the country is primarily from coal. The extraction of coal reserves also contributes to environmental degradation from the coal mining activities and air emissions from coal combustion. (Mpheya and Held, 1999)

- Sulphur oxides (SO_2 and SO_3) presented as SO_x are recognised air pollutants in South Africa. The bulk of sulphur oxides generated and emitted into the atmosphere in the country are released during crude oil processing, coal combustion in thermal power stations and from the combustion of crude oil based products such as HFO and diesel. Sulphur oxides have become a major health concern as they are produced in relatively large quantities from the combustion of HFO in refinery operations and other industrial applications situated close to relatively densely populated residential areas. (Linde, 1999; Diab and Matooane, 1999; Cairncross and Manuel, 1999)

- The burning of fossil fuels in South Africa in both large industrial applications such as power stations as well as in domestic utilities, such as coal and paraffin stoves result in the release of large quantities of particulate emissions. Particulate emissions are not only a nuisance, but are recognised as significant contributors to the recorded cases of upper and lower respiratory illnesses in South Africa. (Terblanche et al, 1994)

- NO and NO_2 collectively known as NO_x are produced from the oxidation of atmospheric nitrogen in high temperature combustion systems. In South Africa NO_x come from sources such as spark and compression ignition engines and fuelled power plants. NO_x contribute to the formation of photochemical smog. For example NO_x contribute significantly to the visible brown haze which occurs in Cape Town.

- Lead (Pb) is a highly toxic heavy metal which within the human body damages the nervous system, circulatory and blood forming system, reproductive system, kidneys as well as producing a wide variety of symptoms and disorders (Kazan, 2000). As discussed in Chapter 2, it is a priority contaminant in used oil, and may be released from the burning of untreated and reprocessed used oils. Management scenarios which will minimise lead emissions would be preferred.

7.3 PRESENTATION AND ANALYSIS OF SELECTED INVENTORY RESULTS

The life cycle inventory results generated for the selected used oil management scenarios are presented in Table 7.2. These inventory results are based on an aggregation of all the contributing flows over the entire life cycle of each used oil management scenario.

The inventory results presented in Table 7.2 show differences in the flow quantities for the resource use and environmental burden flows when compared for the selected used oil management scenarios. An important factor to note in interpreting the inventory results is that some of the flow quantities calculated for the used oil burning scenarios are negative.

In used oil management scenarios where treated or untreated used oil is burned as a fuel, the used oil substitutes an equivalent energy quantity of HFO that would have been burned in the application. In substituting the burning of HFO in the given application, the burning of used oil consequently results in the avoiding of impacts that would be associated with the production and combustion of the equivalent energy quantity of the HFO. The avoided impacts of HFO production and combustion are thus the environmental gains for burning used oils, and they are subtracted from the life cycle burdens of used oil burning.

When negative inventory results are generated for a given inventory flow, as is the case with some results presented in Table 7.2 as well as Appendix 4, the result implies that the burden associated with the respective flow is greater for HFO production and combustion, than would result from substituting with an equivalent energy quantity from burning used oil. Hence, for the negative flow, substituting HFO with used oil would result in a net reduction in the consumption or release of the flow to the environment.

In assessing and comparing any two used oil management scenarios based on an inventory flow, it will be assumed that the used oil management scenario that is associated with the lower quantity of the inventory flow has a superior environmental performance. This proposed basis for comparing environmental performance will be used to assess recycling versus energetic use benefits, (7.3.1) and also to consider the differences between the selected burning/energetic use scenarios, (7.3.2).

7.3.1 Comparing Recycling and Energetic Use Scenarios

The results presented in Table 7.2 show that the consumption of used oil as a fuel in the selected used oil burning scenarios yields a better environmental performance compared to re-refining for the consumption of coal and water as well as the release to the environment of particulates, sulphur oxides and the disposal of chemically polluted effluent. This superior environmental performance of the selected burning scenarios for the respective inventory flows is largely as a result of the environmental gains from the avoided impacts of HFO production and combustion.

Table 7.2 Inventory results for the selected used oil management scenarios based on a functional flow of 1000kg of collected oil

Flow	Units	burning untreated oil in industrial furnace	burning untreated oil in a cement kiln	burning reprocessed oil in industrial furnace	burning reprocessed oil in brick kiln	re-refining used oil
(r) Coal (in ground)	kg	-47.5	-47.5	1.9	1.9	39.4
Water Used (total)	litre	-270	-270	6674	6674	10571
E Fuel Energy	MJ	13982	13982	20915	20915	9175
(a) Lead (Pb)	g	1440.6	214.1	22.3	13.5	1.8
(a) Nitrogen Oxides (NO_x as NO_2)	g	5660	5760	8660	8660	3588
(a) Particulates (unspecified)	g	-1451	-1426	-176	-232	846
(a) Sulphur Oxides (SO_x as SO_2)	g	-41679	-31299	-29169	-15432	5155
(w) Oils (unspecified)	g	13284	13284	13309	13309	1832
(w) Water: Chemically Polluted	litre	-3192	-3192	-1789	-1789	428

However, re-refining also shows better environmental performance compared to the used oil burning scenarios for some of the inventory flow presented in Table 7.2. Unlike the burning options where environmental gains are a result of the avoided impacts of HFO production, the environmental benefits of re-refining come from the recycling of base oils as well as from the reduction in the flow quantity for inventory results whose values are influenced mainly by their content as contaminants in used oil at the point of utilisation. A good case illustrating the latter point is lead emissions, the main origin of which is a contaminant in used oil and for which the avoided impacts of HFO production and combustion does not give any significant benefits.

The assumed influences of re-refining to the fuel and base oil refinery operations in South Africa as described in Chapter 5 imply the recycling of base oils would reduce the quantity of base oils produced in the base oil refineries consequently reducing its scale of operation and the release of concomitant environmental burdens. Re-refining would also reduce the environmental burdens based on the proposed allocation rules for assigning burdens to crude oil extraction. The potential for re-refining to reduce environmental burdens and resource use flows in a used oil management life cycle system is thus dependent on the extent to which recycling reduces the burdens allocated to base oil production and crude oil extraction.

The environmental burdens associated with base oil production were allocated to the base oil product using an economic value based allocation formula. It was assumed that the base oils contribute to 80 % of the total economic value of all the products coming out of the base oil refinery. The sensitivity of inventory results to changes in this allocated economic value will be presented in section 7.5.

7.3.2 Comparing the Selected Used Oil Burning Scenarios

The results in Table 7.2 show differences in the environmental performance of the selected used oil burning scenarios. The following factors have been identified as influencing the differences in the inventory results:

7.3.2.a The extent of processing prior to utilisation as a fuel

This factor distinguishes the environmental performance of scenarios where used oil is burned without prior treatment to scenarios where reprocessed oil is burned. The treating of used oil prior to burning as a fuel reduces the quantity of oil that is ultimately utilised, as an asphaltic bottoms product is discarded during processing. This consequently influences the magnitude of equivalent energy benefits derived from the avoided impacts of HFO production and combustion.

In addition to reducing the benefits derived from the avoided impacts of HFO production and combustion the processing of used oils requires greater utility inputs, resulting in magnified environmental consequences from utilities provision. This is reflected by the inventory results for total water use, fuel energy consumption and nitrogen oxides emissions presented in Table 7.2.

7.3.2.b The extent of contaminants capture in the fired product

This factor can be used in distinguishing the performance of individual energetic use scenarios, but may also be used for distinguishing the energetic use scenarios where used oil is burned in furnaces to those where it is burned in kilns.

When used oil is burned in furnaces it can be assumed that all the contaminants contained in the oil are emitted in the stack. However, in the burning of used oil in kilns the products of used oil combustion come into direct contact with the product stream and some of the contaminants either react with or are trapped in the product matrix. The burning of used oil in cement or brick kilns results in various extents of encapsulation of the used oil contaminants, and this is observed when considering the results for lead and sulphur dioxide emissions in Table 7.2.

Results of the experimental work done by Berry et al (1975) described in section 5.5.1 showed that about 89% of the lead in the system, most of which comes in the used oil is retained in the process solids. The free lead, which is not fixed in the product, in this study was assumed to be emitted through the stack. In practice pollution abatement equipment such as electrostatic precipitators or bag houses are used to severely restrict the particulates emitted, consequently presenting scope for improving the performance of the cement kiln system as regards containing lead emissions. The results for sulphur oxides emissions are discussed in section 7.4.2.

7.4 IDENTIFICATION OF MAJOR CONTRIBUTORS

By identifying the life cycle sub-stages that make the most significant contributions to the total quantity generated for each inventory flow and finding methods of minimising the flow in these life cycle sub-stages improvements may be made to the environmental performance of the selected scenarios.
The life cycle sub-stages of used oil management stages that influence the outcome of LCA inventory results can be taken to consist of the following sub-stages:

- Crude oil extraction and fuels refinery processing.
- Base oil refineries processing.
- Used oil recycling, encompassing the treatment and ultimate use/disposal operations.

The inventory flow contributions for the proposed life cycle sub-stages are presented in Table 7.3 for the three inventory flows discussed in sections 7.4.1 to 7.4.3. The life cycle sub-stages are composed of associated sub-sub-stages as presented in Figure 6.2 and the inventory flow value presented for each sub-stage will be an aggregated value, adding up the contributing quantities of the sub-sub-stages inventory flows. The results presented in Table 7.3 show the relative contributions of the life cycle sub-stages excluding the avoided impacts. Owing to a similarity in the trends observed from analysing the presented inventory flows the following select inventory flows will be used in the analyses in sections 7.41 to 7.4.3:

- Water Used (total)
- (a) Sulphur oxides
- (w) Oils (unspecified)

7.4.1 Water Used (total)

The volume of water used over the life cycles of the selected used oil management scenarios, presented in Table 7.2 and Figure 7.1 show that water consumption increases with extent of treatment the used oil undergoes before ultimate use. By considering the two used oil management scenarios in which used oil is burned without prior treatment, i.e. burning in untreated oil in an industrial furnace or in cement kilns, it can be deduced that HFO production and combustion consume an almost equal quantity of water compared to the burning untreated oil scenarios. This almost equivalent water use for the alternative systems will imply that water use can be assessed for all used oil burning scenarios by considering only the upstream water use of the reprocessing and burning plants.

The Revivoil reprocessing and re-refining configurations consume disproportionately high volume of water when compared other stages of the system life cycle. This fact is illustrated by the comparison of the material and utility requirements for producing 1000kg of base oil from the refinery system to the re-refining system as presented in Table 7.4 The data for water consumption in the Revivoil Processes is presented in a number of publications (Viscolube Marketing Brochure, 1999: Giovanna et al, 1999), and was assumed to be accurate. If it is assumed that the water demands of the Revivoil reprocessing and re-refining configurations can be significantly reduced, their performance compared to options where used oil is burned untreated will improve.

Table 7.3 The inventory flow contributions for the proposed life cycle sub-stages of the selected used oil management scenarios

flow	Burning untreated oil-furnace		Burning untreated oil-cement kiln		Burning reprocessed oil-furnace		Burning reprocessed oil-brick kiln		Re-refining used oil	
	quantity	%	quantity	%	quantity	%	quantity	%	quantity	%
Water Used (total)										
• Fuels refinery stage	2359	46.0	2359	46	2539	22.2	2539	22.2	424	4.0
• Base oil refinery stage	2771	54	2771	54	2771	26.1	2771	26.1	378	3.6
• Recycling stage	0	0	0	0	5485	51.7	5485	51.7	9769	92.4
Total	5130	100	111.3	100	10615	100	10615	100	10571	100
(a) Sulphur Oxides (SO_x) (g)										
• Fuels refinery stage	8445	24.9	8445	54.1	8445	32.1	8445	44.9	1520	29.5
• Base oil refinery stage	5134	15.2	5134	32.9	5134	19.5	5134	27.3	701	13.6
• Recycling stage	20286	59.9	2029	13.0	12716	48.4	5229	27.8	2934	56.9
Total	33865	100	15608	100	26295	100	18808	100	5155	100
(w) Oils (unspecified) (g)										
• Fuels refinery stage	147	1.1	147	1.1	147	1.1	147	1.1	26.5	1.4
• Base oil refinery stage	13228	98.9	13228	98.9	13228	98.9	13228	98.9	1806	98.6
• Recycling stage	0	0	0	0	0	0	0	0	0.1	0
Total	13375	100	13375	100	13375	100	13375	100	1832.6	100

Re-refining of base oil would result in decreased water use in the base oil refinery but would not reduce water use for the re-refining plant. The maximum reduction in water use that can be derived from re-refining is thus equivalent to the total water use of the base oil refinery and for this reason it can be concluded that improving the water use performance of any re-refining technology to the position where it is comparable to the water use for untreated used oil burning scenarios is not possible.

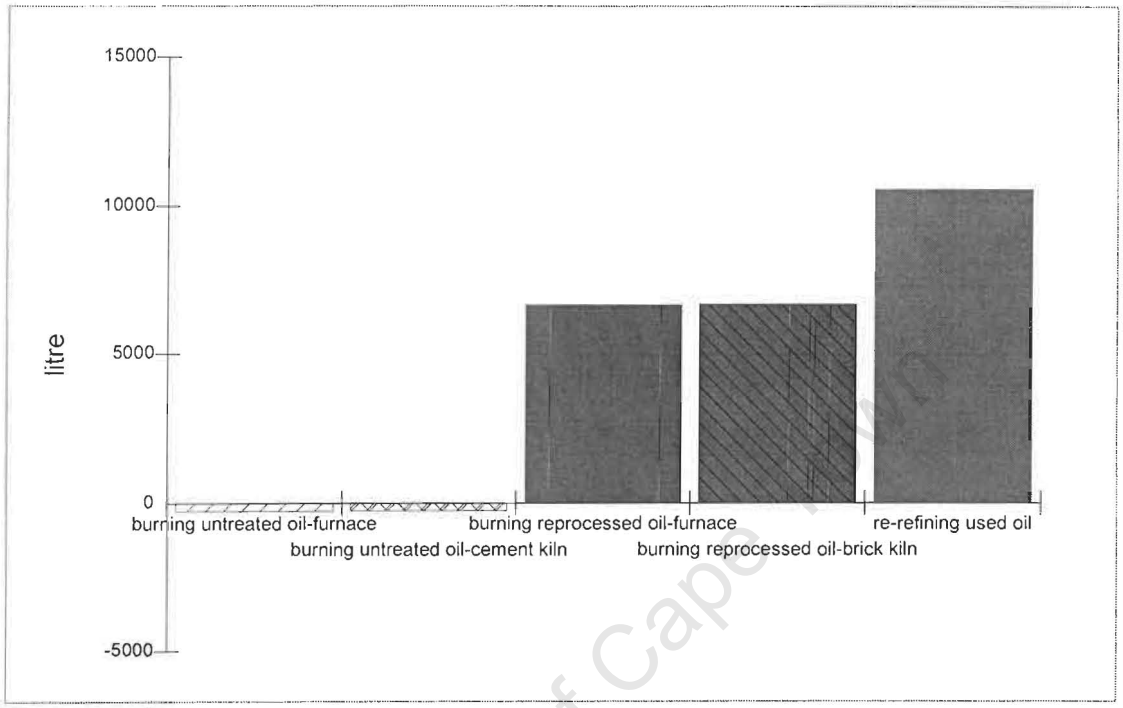


Figure 7.1 Life cycle inventory results for total water used for the selected used oil management scenarios (Results are based on a functional flow of 1000kg of collected oil)

Table 7.4 Material and utility requirements for producing 1000kg of base oil for the South African refineries and the Revivoil re-refining process

flow	Lube oil production (fuels refinery + base oil refinery)	Revivoil Re-refining process
Electricity (MJ)	742	182
Fuel Energy (MJ)	12540	2509
Steam (kg)	1894	1000
Water use (kg)	3281	11955
Propane (kg)	2.56	1.1
SO_2 emissions (kg)	10.1	2.9
Waste water (kg)	1012	213

7.4.2 Sulphur Oxides (SO_x as SO_2)

The inventory results presented in Table 7.2 and Figure 7.2 for sulphur oxides emissions show that the HFO production and combustion emit larger quantities of sulphur oxides than all the used oil burning scenarios. The results show that lowest SO_x emissions would be achieved over

the system life cycle if untreated used oil were to replace HFO in industrial furnaces, resulting in the largest marginal reduction in emissions from avoided HFO emissions. The quantity of sulphur oxides emitted from a system is dependent on the sulphur content of the materials in process and the sulphur content of the fuels that are burned. In the systems considered in the study, fuel energy was supplied mainly from 3 sources; HFO, used oil products and fuel gas. HFO produced in South Africa has a sulphur specification of about 3% (see Table 5.4), used oil products will contain about 1% sulphur (see Table 4.1) and fuel gas contain about 0.02% sulphur by mass (SAPREF, 1999). The used oil recycling systems emit less sulphur oxides compared to HFO production and combustion because they fire a higher proportion of fuel gas in their operations compared to the HFO system and in addition to this HFO combustion releases relatively larger quantities of SO_x. (see Appendix F for system SO_x balances, Appendix G for the HFO production and combustion SO_x balance)

Over the system life cycle the SO_x emissions resulting from burning untreated used oil in industrial furnaces are less than SO_x emissions from burning reprocessed oil in industrial furnaces. However the results of burning used oils in industrial furnaces, presented in Table 5.8 show that the burning of reprocessed oil in an industrial furnace results in lower SO_x emissions compared to burning untreated oil.

These results illustrate one of the strengths of comparative LCA analysis in that the environmental assessment of the systems over their life cycles will reveal benefits and areas of improvement that would not be identifiable from site-specific comparisons. The apparent superior environmental performance of the scenario where untreated used oil is burned in industrial furnaces is because the reprocessing of used oil requires fuel energy inputs for direct firing and steam production. In the study it was assumed that the energy demands of the reprocessing plant would be met by burning the low sulphur reprocessed product, resulting in further emissions of the sulphur contained in the fuel as SO_x. In addition, reprocessing yields a smaller quantity of oil for burning as it discards an asphaltic bottoms product. The smaller quantity of oil ultimately produced as a fuel compared to untreated burning has correspondingly reduced benefits form avoided impacts of HFO production and combustion. The trade offs in sulphur oxides emissions at different life cycle stages for the two burning options are illustrated using a sulphur oxides balance sheet presented in Table 7.5.

The reduction of sulphur emissions during the burning of reprocessed oil could thus be achieved by reducing the energy demands of the reprocessing plant and by also burning fuels with low sulphur emissions over their life cycles.

The burning of oil in kilns, both cement and brick, results in reduced environmental gains from HFO production and combustion when compared to the burning of oil in industrial furnaces. In the burning of oils in kilns where the alkaline process solids come into direct contact with the products of combustion, sulphur oxides are retained in the product matrix as a result of chemical reactions between the solids and the sulphur oxides. (Berry et al, 1975; J Muller Reports, 1999) A typical reaction in the kiln would involve calcium oxides in the cement raw meal of brick with sulphur oxides to form calcium sulphates. Experimental tests done with the burning of HFO in both brick and cement kilns showed that over 50% of the sulphur in the oil is retained in the system solids. (Berry et al, 1975; BP Laboratory Report, 1984; De Hoop Bricks Report, 1995) It was assumed, in the study, that these observations would be applicable for the burning of used oil and used oil products, and that a similar sulphur oxides retention capacity would be applicable. However, there is a possibility that in practice a greater proportion of the sulphur oxides in would be fixed into product matrix when burning used oil as the alkaline process solids would have a greater retention potential owing to the lower sulphur content. There is scope for future experimental work to investigate parameters such as reaction mechanism, residence time, and other factors known to influence solid-gas reactions for the observed sulphur retention in kilns, thereby identifying opportunities for improving their environmental performance.

Table 7.5 Balance sheet for sulphur oxides emissions for the life cycle sub-stages for the burning of untreated and reprocessed oil in industrial furnaces

Life cycle sub-stage	Burning untreated used oil Industrial furnace	Burning reprocessed oil Industrial furnace
Crude extraction + fuels refinery + base oil refinery (kg SO_x)	*13.5	*13.5
Reprocessing of used oil + (kg SO_x)	0.0	1.1
Burning + collected/reprocessed oil (kg SO_x)	20.4	11.6
Sub-total (kg SO_x)	**33.9**	**26.2**
- Credits from HFO production (kg SO_x)	-22.2	-16.2
- Credits from HFO burning (kg SO_x)	-53.5	-39.2
Final SO_x emissions (kg)	**- 41.8**	**- 29.2**

* based on allocation rules for respective sub-stages
see Appendix G for balance calculations

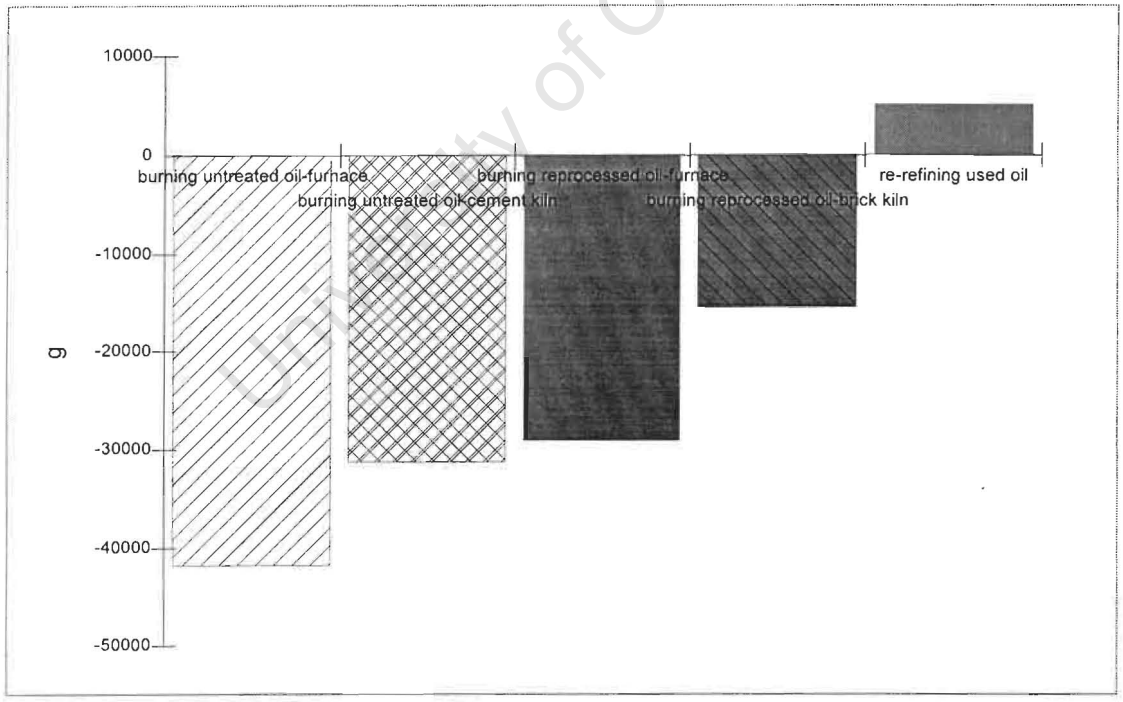


Figure 7.2 Life cycle inventory results for sulphur oxides (SO_x) emissions for the selected used oil management scenarios (Results are based on a functional flow of 1000kg of collected oil)

7.4.3 Oils (unspecified)

The inventory results quantifying the oils released to water ((w) Oils (unspecified)) for the selected used oil management scenarios, presented in Table 7.2 are also presented using a bar chart in Figure 7.3

These results show that the re-refining of used oil would result in a significant reduction of oils released to water. All the used oil burning scenarios would result in an almost equal, relatively large positive release of oils to water.

The significantly superior performance of the re-refining scenario is because the largest quantity of oils are released to water in the base oil refinery plant. Re-refining reduces the scale of operation of the base oil plant consequently reducing the quantity of oils released to water. It can also be deduced from the results that the production and combustion of HFO does not release significant quantities of oily water to the environment as the avoided impacts of HFO production and combustions do not significantly improve the used oil burning scenarios' capacity to reduce the quantity of oily water produced.

The overall performance of the spectrum of selected used oil management scenarios with regards to reducing the amount of oils released in the effluent would be improved by introducing better methods of mitigating against the release of oils to water in the base oil refinery plants.

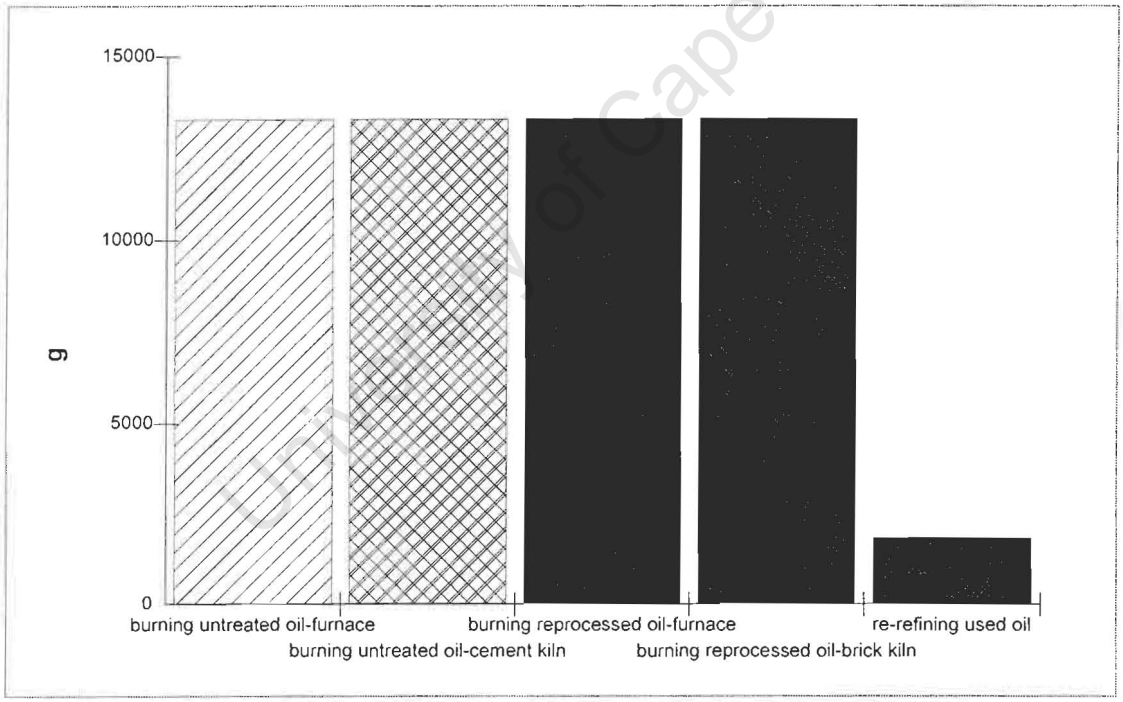


Figure 7.3 Life cycle inventory results for the release of oils into effluent (w) Oil (unspecified) for the selected used oil management scenarios (Results are based on a functional flow of 1000kg of collected oil)

7.5 SENSITIVITY ANALYSIS

SAPREF Technical Oil Cooking Course (1999) data for base oil production indicates that base oil output is about 2 % by mass of the total refinery output but the base oil refinery and its attached fuels refinery contribute about 22 % of the gross refinery earnings. From this data it would be expected that base oils contribute a relatively high proportional economic value of the base oils refinery products spectrum which include waxes and asphalt. For this reason an economic value based allocation of the base oil re-refinery environmental burdens was used and a proportional base oil economic value of 80% was assumed.

It could be argued that allocating a larger proportion of the refinery system's environmental burdens to the base oil product would increase the burdens associated with the energetic use scenarios, reducing the benefits that would be derived from avoiding the impacts of HFO production and combustion, hence making re-refining more competitive on those inventory flows it gave inferior results. Conversely, for those inventory flows in which re-refining yields better results a lower economic value allocation factor would improve the competitiveness of the energetic use scenarios.

The extent of improvement that could be derived from either lowering or increasing the economic value allocation factor were assessed by carrying out a sensitivity analysis of the inventory results to allocation factors of 95% and 65 %. The results of these sensitivity analyses are presented in Tables 7.6 and 7.7 In the case where an allocation factor of 95 % is selected, the following allocation formulas for the base oil refineries and crude oil extraction were used, respectively:

$$\begin{pmatrix}\text{environmental}\\ \text{burden}\end{pmatrix}_i = 0.95 * \begin{pmatrix}\text{total base oil}\\ \text{refinery environmental}\\ \text{burden}\end{pmatrix}_i$$

$$\begin{pmatrix}\text{enviro}\\ \text{burden}\\ \text{crude extraction}\end{pmatrix}_i = 0.95 * \left\{\left(\frac{M_C + M_D + [M_{\text{fuel gas}}]}{M_A}\right)\right\} * \begin{pmatrix}\text{total}\\ \text{enviro}\\ \text{burden}\\ \text{crude extraction}\end{pmatrix}_i$$

The inventory results presented in Table 7.6 indicate that increasing the economic value allocation factor of base oils does improve the environmental performance of re-refining, and reduces the gains from avoided impacts of HFO production and combustion for the used oil burning scenarios. The results in Table 7.7 show the improved performance of the energetic use scenarios compared to the re-refining scenario. However increasing or decreasing the economic value allocation factors does not significantly alter the trends in the environmental performance of all the scenarios as already presented in Table 7.2. The results presented in Table 7.6 and 7.7 show that the increasing of the allocated base oil economic value, although offering incremental improvements in the inventory flows for the management scenarios, does not change the overall comparative environmental performance of used oil burning to re-refining options.

The sensitivity analysis that was carried out in the study considered only the effect of allocation rules on the performance of the management scenarios. Another factor that could be tested using sensitivity analyses is the influence of emissions associated with the transportation of used oil to their end-use sites. In the current model the emission contributions of transportation options were considered to be negligible, and since the management scenarios considered in the study were not assigned to specific locations it would be difficult to present accurate transport data. However in future uses of the model to compare alternative scenarios whose location is defined, emissions associated with used oil transportation could be considered.

Table 7.6 Inventory results for the selected used oil management scenarios based on a functional flow of 1000kg of collected oil, using an economic value based allocation of 95 % in the base oil refineries

Flow	Units	burning untreated oil in industrial furnace	burning untreated oil in a cement kiln	burning reprocessed oil in industrial furnace	burning reprocessed oil in brick kiln	re-refining used oil
(r) Coal (in ground)	kg	-26.6	-26.6	22.8	22.8	42.6
E Fuel Energy	MJ	19987	19987	26921	26921	10141
Water Used (total)	litre	691.8	691.8	7635.9	7635.9	10721
(a) Lead (Pb)	g	1440.7	214.2	22.4	13.6	1.8
(a) Nitrogen Oxides (NO_x as NO_2)	g	8301.9	8401.9	11302.0	11302.0	4019
(a) Particulates (unspecified)	g	-926.6	-901.6	348.3	292.8	928
(a) Sulphur Oxides (SO_x as SO_2)	g	-39223	-29379	-26623	-12886	5572
(w) Oils (unspecified)	g	15792.2	15792.2	15816.7	15816.7	2177
(w) Water: Chemically Polluted	litre	-2863.8	-2863.8	-1460.9	-1460.9	477

Table 7.7 Inventory results for the selected used oil management scenarios based on a functional flow of 1000kg of collected oil, using an economic value based allocation of 65 % in the base oil refineries

Flow	Units	burning untreated oil in industrial furnace	burning untreated oil in a cement kiln	burning reprocessed oil in industrial furnace	burning reprocessed oil in brick kiln	re-refining used oil
(r) Coal (in ground)	kg	-68	-68	-19	-19	36
Water Used (total)	litre	-1232	-1232	5712	5704	10421
E Fuel Energy	MJ	7976	7976	14910	14910	8209
(a) Lead (Pb)	g	1441	214	22	13	2
(a) Nitrogen Oxides (NO_x as NO_2)	g	3018	3118	6018	6017	3157
(a) Particulates (unspecified)	g	-1976	-1951	-701	-758	764
(a) Sulphur Oxides (SO_x as SO_2)	g	-44315	-33846	-31715	-17978	4739
(w) Oils (unspecified)	g	10777	10777	10801	10801	1489
(w) Water: Chemically Polluted	litre	-3519	-3519	-2116	-2117	380

7.6 CONCLUSION

The analysis of the selected inventory results presented in Table 7.2 show that LCA reveals differences in the environmental performance of the selected used oil management scenarios. The inventory results were also used in identifying areas of improvement for each of the management scenarios. The results for the selected inventory flows can be used to form a clear distinction between flows for which used oil burning scenarios produce better environmental performance to the re-refining scenario. This is because there is no inventory result in which the re-refining option performed better than only one of the used oil burning scenarios while the remaining burning scenarios produced a superior environmental performance. In other words when the re-refining scenario provides superior environmental performance to the burning scenarios, it will provide superior performance over all the used oil burning scenarios. Conversely, when re-refining provides inferior environmental performance to the burning scenarios, it will provide inferior performance to all the used oil burning scenarios. There is however a comparative difference in the environmental performance of alternative burning scenarios and the comparative environmental performance among the burning options will differ for the inventory flows.

In the majority of the inventory results presented in Table 7.2 the used oil burning scenarios show better environmental performance than the re-refining scenario. However, these results cannot be used to conclusively say the burning options are better than re-refining in the South African context as only nine out of 292 were assessed.

The question of determining the used oil management scenario that has the best overall environmental performance will be considered in Chapter 9 after the environmental performance of the scenarios has been assessed using Life Cycle Impact Assessment (LCIA) in Chapter 8.

Chapter 8

Results of Life Cycle Impact Assessment

8.1 INTRODUCTION AND APPROACH

The purpose of this chapter is to assess the environmental performance of the selected scenarios for used oil management in South Africa using Life Cycle Impact Assessment (LCIA)

In Chapter 7 the environmental performance of the selected used oil management scenarios was assessed using selected life cycle inventory flows. In LCIA the life cycle inventory flow data is assigned to environmental effect or impact categories they contribute to, followed by calculation processes in which characterisation factors are assigned to the flows to convert the life cycle inventory results to common units for aggregation within the impact category. The process of carrying out LCIA was described in section 3.3.3 and the guidelines for on a general framework for LCIA are described in the international standard for LCIA (ISO 14042, 2000).

The assessment of the scenarios will be based on the output related impact categories proposed by SETAC for LCIA (Udo de Haes et al, 1999) which are also presented in Table 3.1. The selected impact categories and the characterisation of their contributing inventory flows are discussed in section 3.3.3. The process of LCIA was carried out on the life cycle inventory data generated from the computational model relating the scenarios and the impact assessment process was carried out using the TEAM™ 3 tools for LCIA.

In this chapter the LCIA results of the comparative assessment of scenarios for used oil management shall be presented and discussed for each of the selected category indicators. The LCIA results of each impact category will be presented for analysis using a graphical mode. The results will be presented using bar charts for the life cycle impact category indicators, which will enable the identification and discussion of the major contributors to the impact category.

After the presentation and analysis of the LCIA results for the selected category indicators the LCIA results will be discussed with the aim of assessing the overall environmental performance of the selected used oil management scenarios and proposing the most environmentally sound route for used oil management in South Africa.

In the conclusions the findings of the LCIA will be summarised and the results of the LCIA based assessment will be compared to the findings from the life cycle inventory flow based assessment presented in Chapter 7. Similarities and differences of results from the two assessment methods will be reviewed.

8.2 INTERPRETATION OF LCIA RESULTS

There are a number of different life cycle impact assessment categories on which the results of LCA may be interpreted. However, the working group on LCIA of SETAC-Europe proposed a list of impact categories for LCIA. (Udo de Haes et al, 1999) The results of this study will be presented using the proposed output related impact categories which are:

- Human toxicity,
- Air Acidification,
- Eutrophication,

- Eutrophication,
- Photochemical oxidant formation,
- Ecotoxicity,
- Climate Change (Greenhouse effect).

These LCIA categories are also discussed in section 3.3.3.a. The LCIA results were generated from the TEAM™ 3 tool for impact assessment using impact categories developed by the Centre of Environmental Science (CML). CML is an inter-faculty department of Leiden University that is involved in the development of a standard methodology to determine the environmental effect of products, working in association with the Society for Environmental Toxicology and Chemistry (SETAC) and the International Standards Organisation (ISO). (CML, 2000) The CML method is described in section 3.3.3.a with the description of life cycle impact categories.

In presenting the LCIA results in a graphical format, a legend containing the major contributing flows is also given. It must be noted that the LCIA results are not based on these major contributing flows only, but are based on the aggregation of ALL life cycle inventory flows contributing to the respective environmental impact category.

8.2.1 Effects on Human Health

Human toxicity is an important environmental impact category for which there is no unanimity within the environmental assessment of products on any coherent and operational method for a quantitative assessment of toxic substances with equal footing with the emissions of other substances contributing to other environmental impact categories. (Hauschild and Wenzel, 1998) For this reason two different impact evaluation methods, the CML and the CST methods, have been used in assessing the human toxicity potentials of the selected used oil management scenarios. The results from assessing the selected used oil management scenarios based on their potential contributions to human toxicity are given in Figures 8.1 and 8.2.

Both the CML and CST human toxicity assessment methods show the dominance of lead emissions in determining a management scenario's human toxicity potential. The CML results, in addition to showing the dominance of lead ((a) Lead Pb), also indicate that sulphur oxides emissions ((a) Sulphur Oxides (SO_x as SO_2) are significant in interpreting each scenario's performance as a contributor to human health effects. The CST method does not characterise sulphur emissions as significant contributors to human health effects. However, in South Africa sulphur oxide emissions are publicly recognised as an important contributor to negative human health effects (MBendi, 2000; Linde, 1999; Diab and Matoone, 1999; SAPREF, 1999) and for this reason the CML results will be used for the overall assessment of human toxicity potentials. The CML and CST determined results show that lead emissions, even though having an insignificant mass contribution to total emissions, are highly toxic, having significant influence on the human toxicity potential of a management scenario.

The results presented using the CML method show that the used oil burning scenarios would have reduced human toxicity potentials from avoiding the impacts of HFO production and combustion which incur the release of sulphur oxides.

An analysis of the inventory results shows that the largest sources of lead emissions in the used oil management life cycles is at the recycling stages where lead may be emitted during the burning of used oils. The other life cycle stages of the selected used oil management scenarios make an insignificant contribution to lead emissions.

The re-refining management scenario emits the smallest quantities of lead and has the lowest potential for contributing to human toxicity from lead emissions into the atmosphere.

When used oil is burned as a fuel, the scenarios in which the oil is reprocessed prior to burning offer better environmental performance with regards to minimising the human toxicity potential

when compared to scenarios in which used oil is burned untreated. In the burning of used oil in cement kilns the used oil contaminants have been reported to be encapsulated in the cement product matrix (Berry et al, 1975; McKendry-Smith, 1989). However, a significantly larger proportion of these contaminants, particularly lead, are released when compared to the options where used is reprocessed prior to burning. The burning of used oil in cement kilns would offer competitive performance to the burning of reprocessed oil if stringent air pollution control measures are put in place in the operation.

The burning of reprocessed oil in industrial furnaces presents the largest margin in avoiding the human toxicity impacts of HFO production and combustion emanating from sulphur oxides emissions, and in this respect offers superior performance to re-refining. In comparing the overall human toxicity potential of re-refining and the energetic use scenarios, the two systems would have to be weighed based on the relative gains from a lower lead emissions in re-refining to the margin of avoided sulphur oxides emissions when used oils are burned.

The burning of untreated used oil in industrial furnaces emits virtually all the inorganic and metallic contaminants in the used oil to air. Used oils collected in South Africa have an average lead content of about 0.1% and the emission of this lead to the environment has a significant human toxicity potential as is shown in Figures 8.1 and 8.2. If human toxicity is taken to be the most important environmental performance indicator for the selected used oil management scenarios then it will be recommended that all used oils should either undergo some form of treatment prior to disposal to remove the contaminants, else they should be utilised in industrial applications that either encapsulate or react with the contaminants and preventing them from release as emissions to the environment.

8.2.2 Contributions to Air Acidification

Acidification can be defined as an impact which leads to the fall in a system's acid neutralisation capacity (De Vries and Breeuwsma, 1987) Acidifying substances include NO_x, SO_x and NH_3, and the acidification classification factors are derived from the propensity of a substance to release hydrogen ions (H^+), as compared to SO_2. Air acidification contributes to material degradation or corrosion, with consequent major economic costs. (Hauschild and Wenzel, 1998) Other environmental problems include the acidification related leaching of nutrients from soils and the acidification of water bodies. (Forbes, 1999)

The results showing the acidification potentials of the selected used oil management scenarios are presented in Figure 8.3. These results show that air acidification is influenced on the main by nitrogen oxides emissions ((a) NO_x as NO_2) and sulphur oxides emissions ((a) SO_x as SO_2). Nitrogen oxides are emitted during the combustion of fossil fuels and it would be expected that the greater the life cycle energy demands of a used oil management scenario, the higher its nitrogen oxides related potential for contributing to air acidification. Re-refining has the lowest life cycle energy demands and this is reflected in its comparative nitrogen oxides emissions contributing impacts to air acidification shown in Figure 8.3.

Sulphur oxides emissions are not only influenced by a system's energy demands but also by the sulphur content of the fuels. The inventory results presented in Table 7.2 and the balance sheet for sulphur oxides emissions for presented in Table 7.5 show that HFO production and combustion releases more sulphur oxides than the energetic use scenarios. As discussed in section 7.4.2 these seemingly anomalous results when compared to the inventory results of the fuel energy use related flows are as a results of the burning of a higher fraction of low sulphur fuel gas and reprocessed oil in the energetic use scenarios.

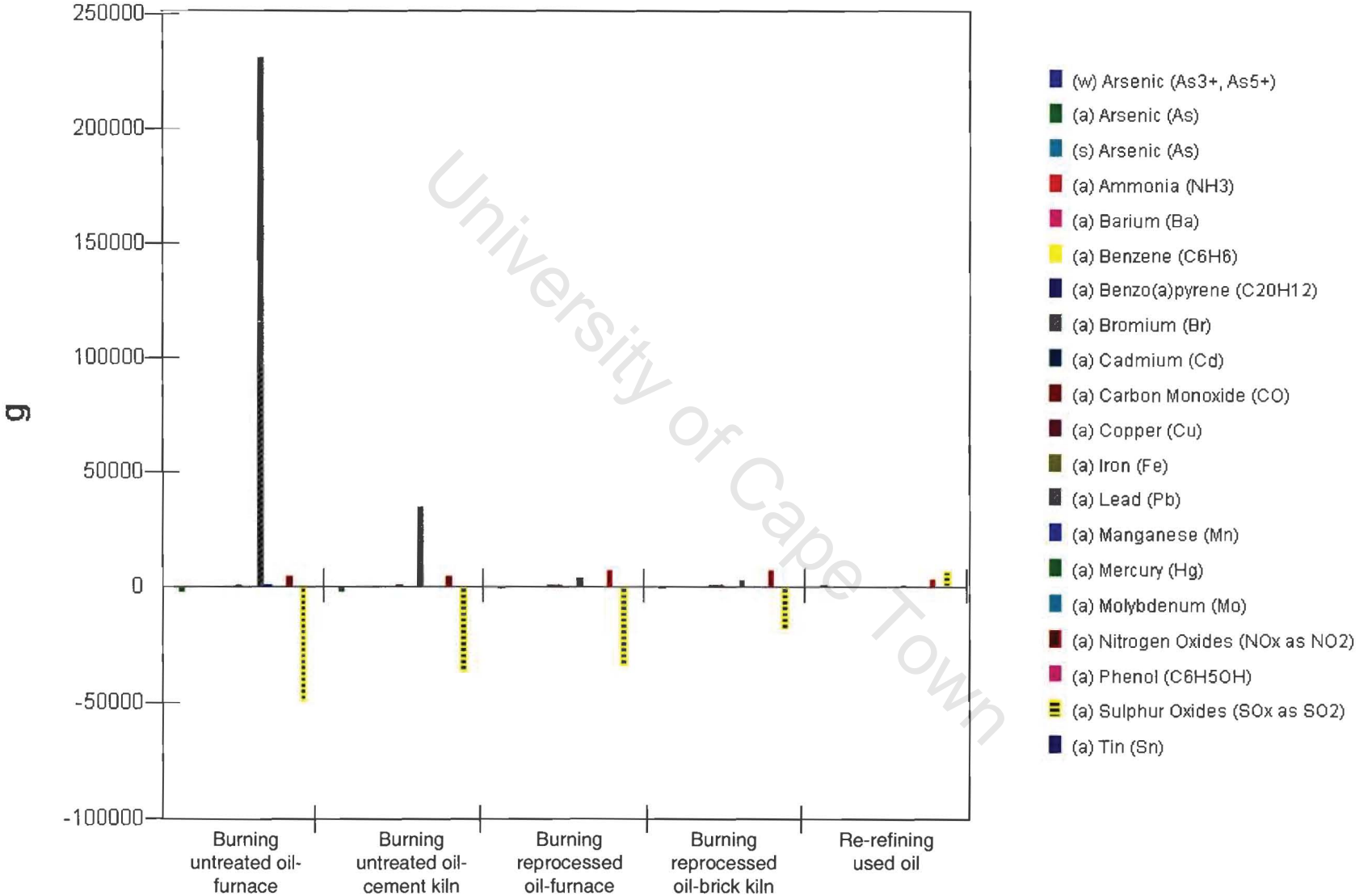


Figure 8.1 CML-Human Toxicity potentials for selected used oil management scenarios

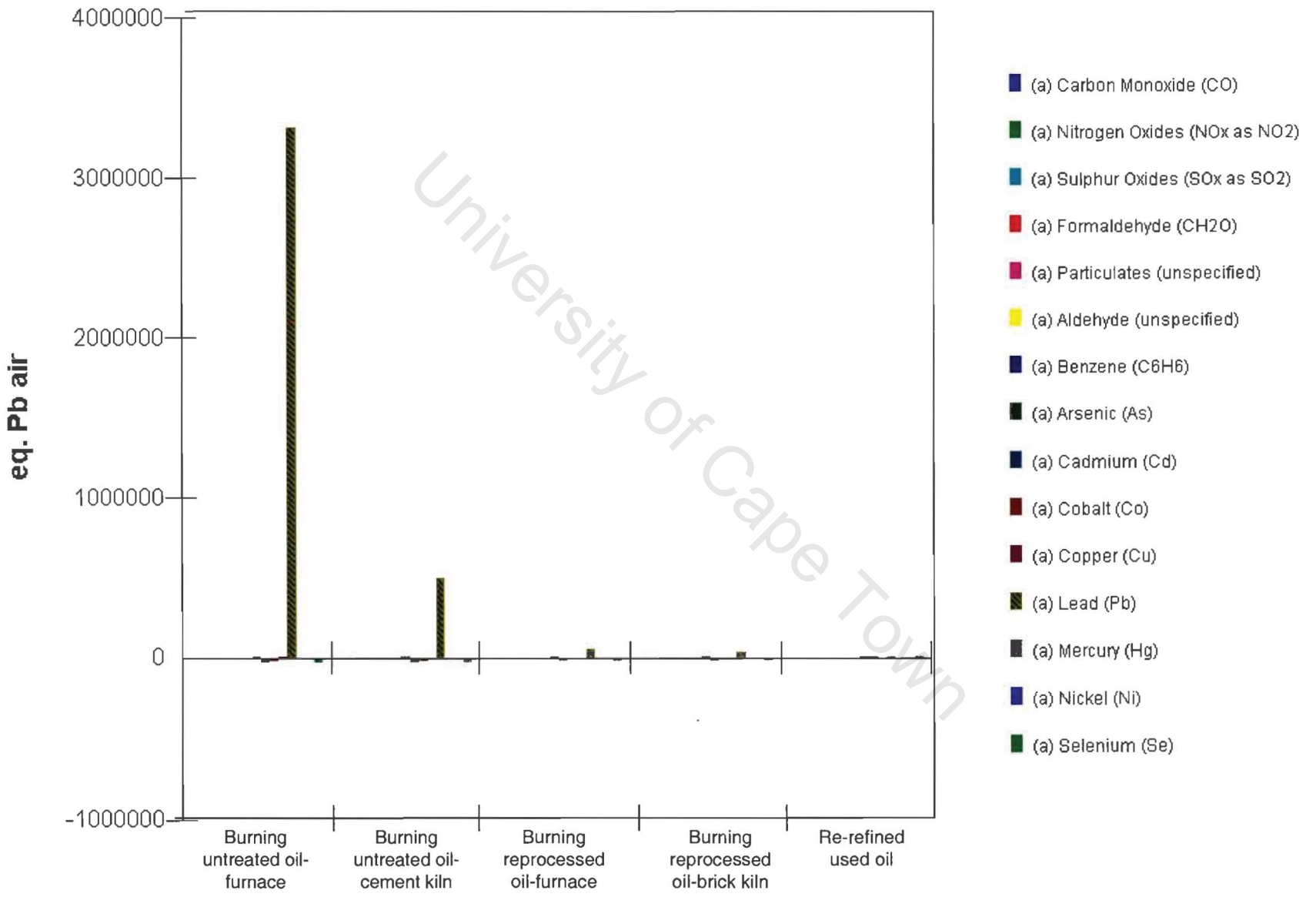


Figure 8.2 CST-Human Toxicity potentials for selected used oil management scenarios

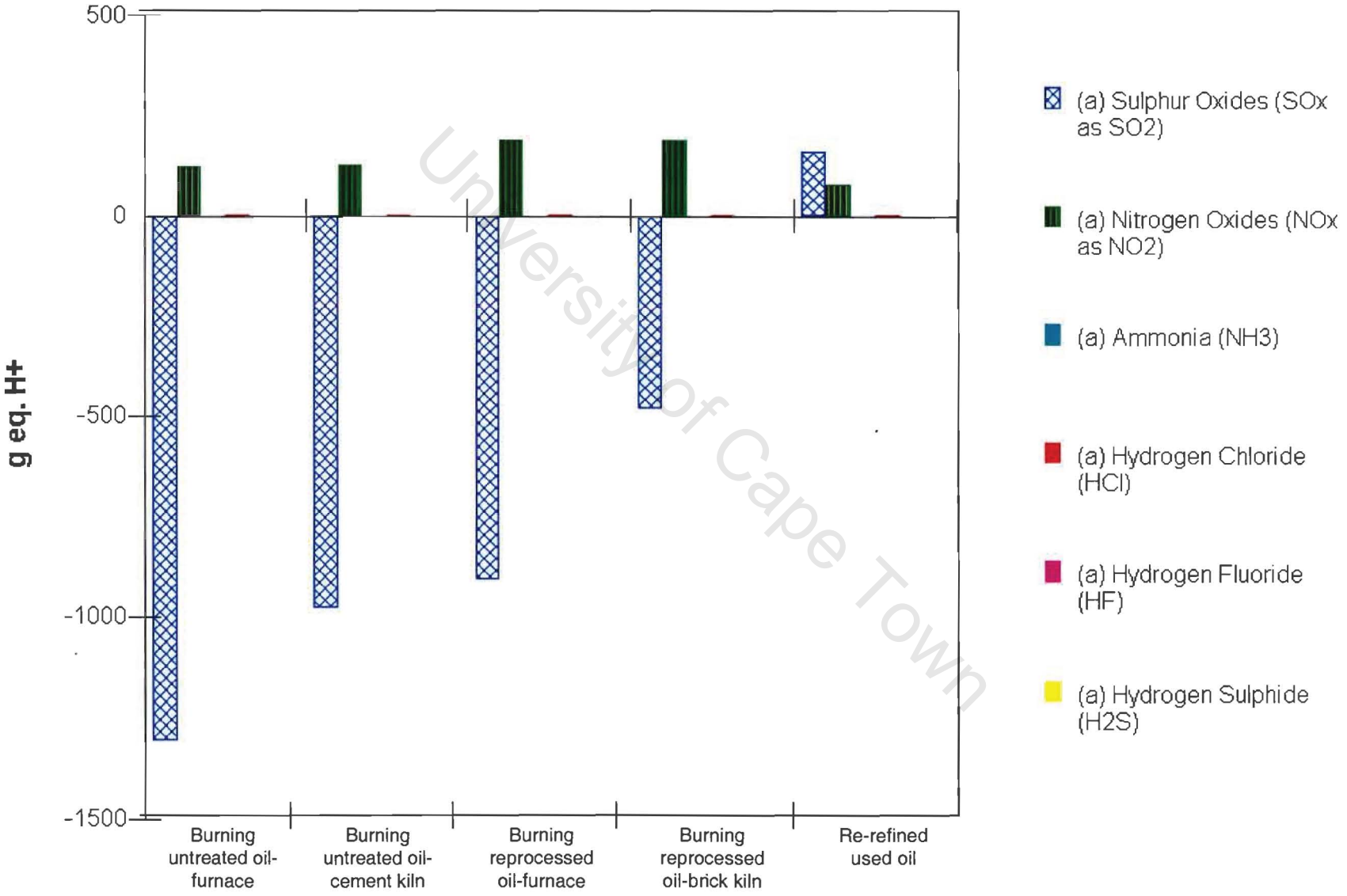


Figure 8.3 CML-Air Acidification potentials for selected used oil management scenarios

The results in Figure 8.3 show that the selection of the used oil burning scenarios would result in the avoidance of evidently dominant air acidification potential that would arise from sulphur oxides emissions during HFO production and combustion. The results show that the energetic use scenarios present better environmental performance than re-refining and they can also be interpreted as showing that the burning of used oil in industrial furnaces without prior treatment would present the least potential for air acidification. It can also be deduced that reducing the life cycle energy uses of the selected scenarios will reduce the air acidification potentials for all the used oil management scenarios.

8.2.3 Eutrophication Potentials

Eutrophication can be described as an enrichment of the aquatic environment with nutrient which leads to an increase in the production of planktonic algae and higher aquatic plants, which in turn leads to reduction in the quality of the water. (Christiansen et al, 1993) Substances that contain the plant growth limiting macronutrients, nitrogen and phosphorous, in a biologically available form are potential contributors to nutrient enrichment. In the calculation of nutrient enrichment potentials for substances, the potentials must be expressed in the form of their contribution of nitrogen or phosphorous. In the results presented in Figure 8.4 using the CML method, the impact potential is expressed as an equivalent release of PO_4^{3-}.

The results of assessing the performance of the selected used oil management scenarios using their eutrophication potential show that re-refining has the best performance. Of the energetic use scenarios, the burning of untreated oil in cement kilns presents the lowest potential for contributing to eutrophication. A comparison of the energetic use scenarios in which used oils are burned in kilns to the scenarios where they are burned in furnaces show that the burning of used oil in cement or brick kilns would result in the encapsulation of phosphate based contaminants that contribute to eutrophication.

The results also show that nitrogen oxide emissions are the dominant contributors to the eutrophication. In the life cycles of the selected used oil management scenarios nitrogen oxides are generated from the combustion of fossil fuels and an overall reduction in energy use would directly reduce eutrophication potentials. The treatment of used oil may also release effluent with high chemical oxygen demand (COD) which contributes to eutrophication. The reduction of effluent COD for these processes would result in a decreased eutrophication potential.

8.2.4 Contributions to Photochemical Oxidant Formation

The photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the troposphere can result in increased concentrations of reactive substances called photo-oxidants, which are injurious to the health of living organisms. The potential contribution to photochemical ozone formation from a substance can be described by its Photochemical Ozone Creation Potential (POCP) and the reference substance is ethylene, C_2H_4.

The results showing the potential contributions of the life cycle inventory flows to photochemical oxidant formation are given in Figure 8.5. The results show that re-refining gives the best performance with regards to minimising photochemical oxidant formation while managing used lubricating oils in South Africa.

Of the energetic use scenarios, the scenarios in which used oil is burned without prior treatment show the best performance for minimising photochemical oxidant formation.

Figure 8.5 shows that the major contributors to photochemical oxidant formation for all the used oil management options are light hydrocarbon, benzene and aldehydes emissions. An analysis of the life cycle inventory data shows that these compounds are emitted at the refinery stages of the lubricating oil life cycle, hence the superior performance of the re-refining scenario resulting from the reduced scale of the base oil refineries operations.

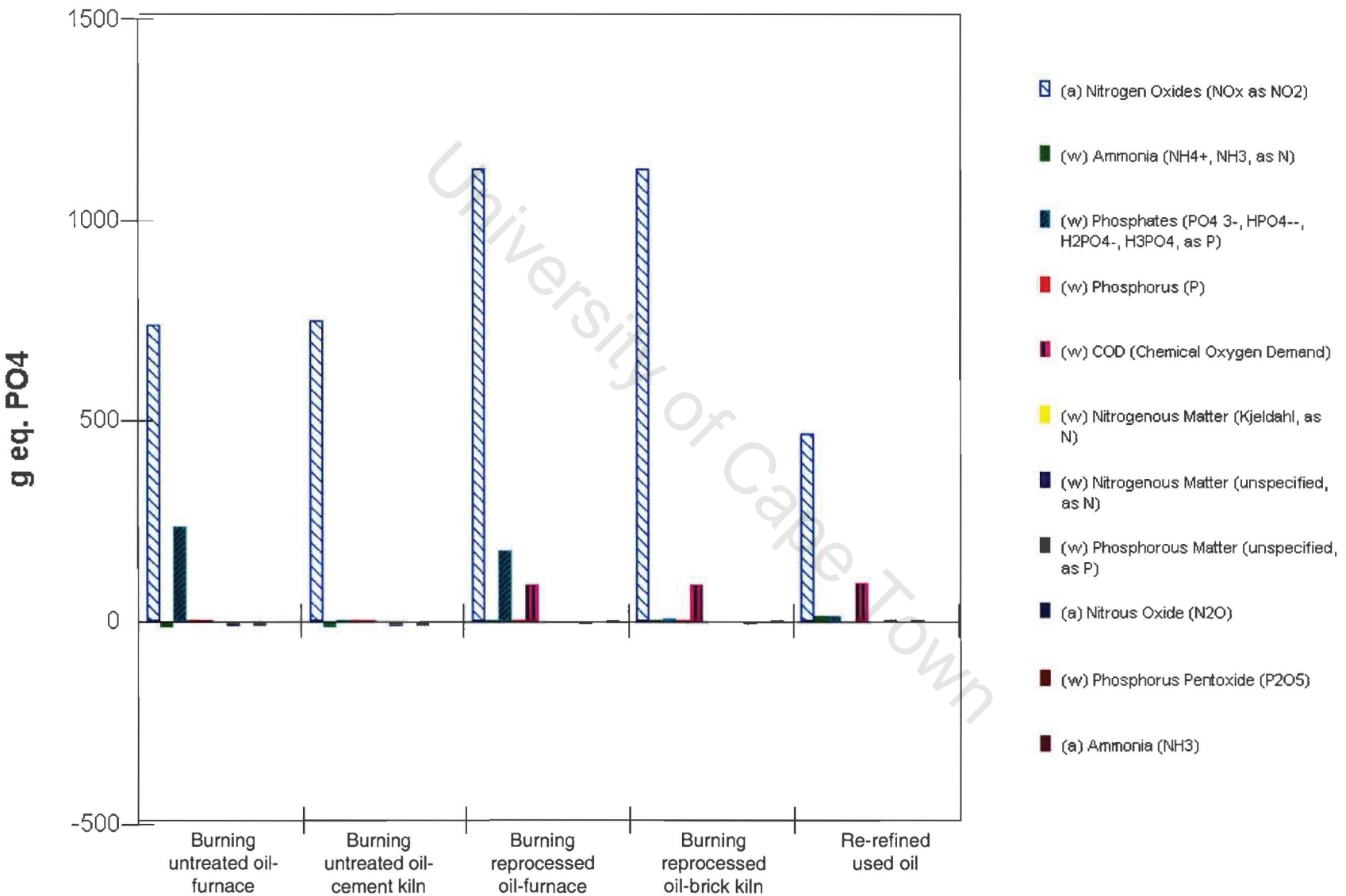


Figure 8.4 CML-Eutrophication potentials for selected used oil management scenarios

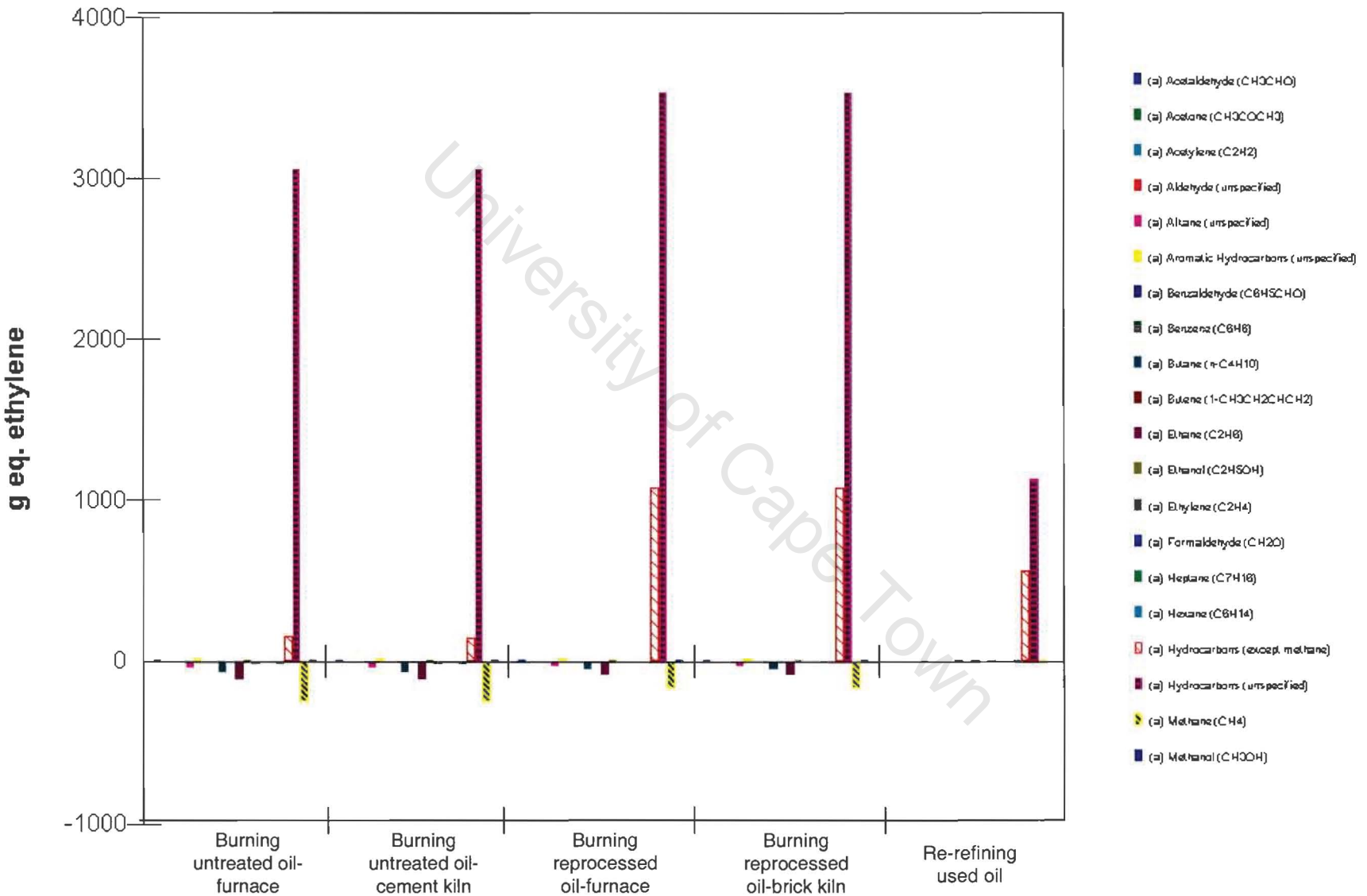


Figure 8.5 WMO-Photochemical oxidant formation (average) potentials for selected used oil management scenarios

8.2.5 The Greenhouse Effect

The greenhouse effect or global warming is the increase in the temperature of the earth's atmosphere form the absorbance of re-emitted infrared radiation by gases, aerosols and particles in the earth's atmosphere. The focus in environmental assessment is on the "man-made greenhouse effect", which is an increase in atmospheric temperature over and above the natural greenhouse effect, caused by man-made emissions of substances or particles which can influence the earth's radiation balance. The most important emissions resulting from human activities which can enhance the greenhouse effect are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons (hydrocarbons containing chlorine, fluorine and bromine). Ozone (O_3) is also a greenhouse gas, but the extent of its contribution is currently uncertain.

The results of assessing the selected used oil management scenarios' potential for contributing to the green house effect are presented in Figure 8.6. The results show that the management scenarios in which used oil is burned without prior treatment appear to have the lowest potential for contributing to the greenhouse effect.

As in the assessment of photochemical oxidants formation, the main factors influencing the performance of the scenarios is the effect of re-refining on the scale of the refinery operations and the benefits on the burning scenarios from the avoided impacts of HFO production.

The results presented in Figure 8.6 show that CO_2 emissions and avoided methane emissions are the major contributing flows to greenhouse effect potentials. CO_2 emissions arise mainly from the combustion of fossil fuels at every life cycle stage of the used oil management scenario. The greater process energy demands are in the refining of lubricating oils hence re-refining reduces the release of greenhouse gases.

However, the results also show that the energetic use scenarios have lower overall greenhouse effect potential than re-refining as a result of the gain that would result from the avoided methane emissions associated with HFO production and combustion. The data module used to in the study for HFO production and combustion is for an average for European processes. This module indicates that about 40 kg of methane is emitted for every 1000kg of HFO produced. The emission of such a relatively high quantity of methane is questionable and is probably as a result of a calculation error. The amount of methane released from HFO production and combustion, although no data is currently available, would be expected to be comparable to the quantities released from the management scenarios under consideration. This would result in significantly reduced benefits from avoided methane emissions. The IPCC allocates an equivalent global warming potential to methane of 62-82 kg CO_2/ kg methane.

The LCIA results obtained for the assessment of greenhouse effect potentials emphasises the need to acquire accurate and directly applicable emissions data for HFO production in South Africa for dependable results to be presented.

8.2.6 Aquatic Ecotoxicity Effects

The results of the assessment of using aquatic ecotoxicity as an environmental performance indicator are presented in Figure 8.7.

The results show a dominance of oils in wastewater ((w) Oils (unspecified)) as a contributor to aquatic ecotoxicity for all management scenarios. Re-refining as the used oil management scenario that would result in the lowest releases of oils in waste waster has the lowest aquatic ecotoxicity potential.

In Chapter 7 oils released in wastewater were discussed in the assessment of selected used oil management scenarios based on life cycle inventory flows. The results of the lifecycle inventory

flows analysis given in Table 7.4 show that the largest release of oils into water occurs in the base oil refinery plant. Re-refining would reduce the scale of operation of the base oil plant, consequently reducing the quantity of oils released in wastewater.

The reduction in the quantities of oil released with effluent at the base oil refinery would reduce the aquatic ecotoxicity potentials of all the management scenarios. The influence of disposing oils in water to aquatic ecotoxicity as presented in Figure 8.7 also give an important insight into the potential damage to aquatic life forms that is resulting from the improper disposal of the large proportion of uncollected oils in South Africa and gives support to intensification of the waste oil collection programs.

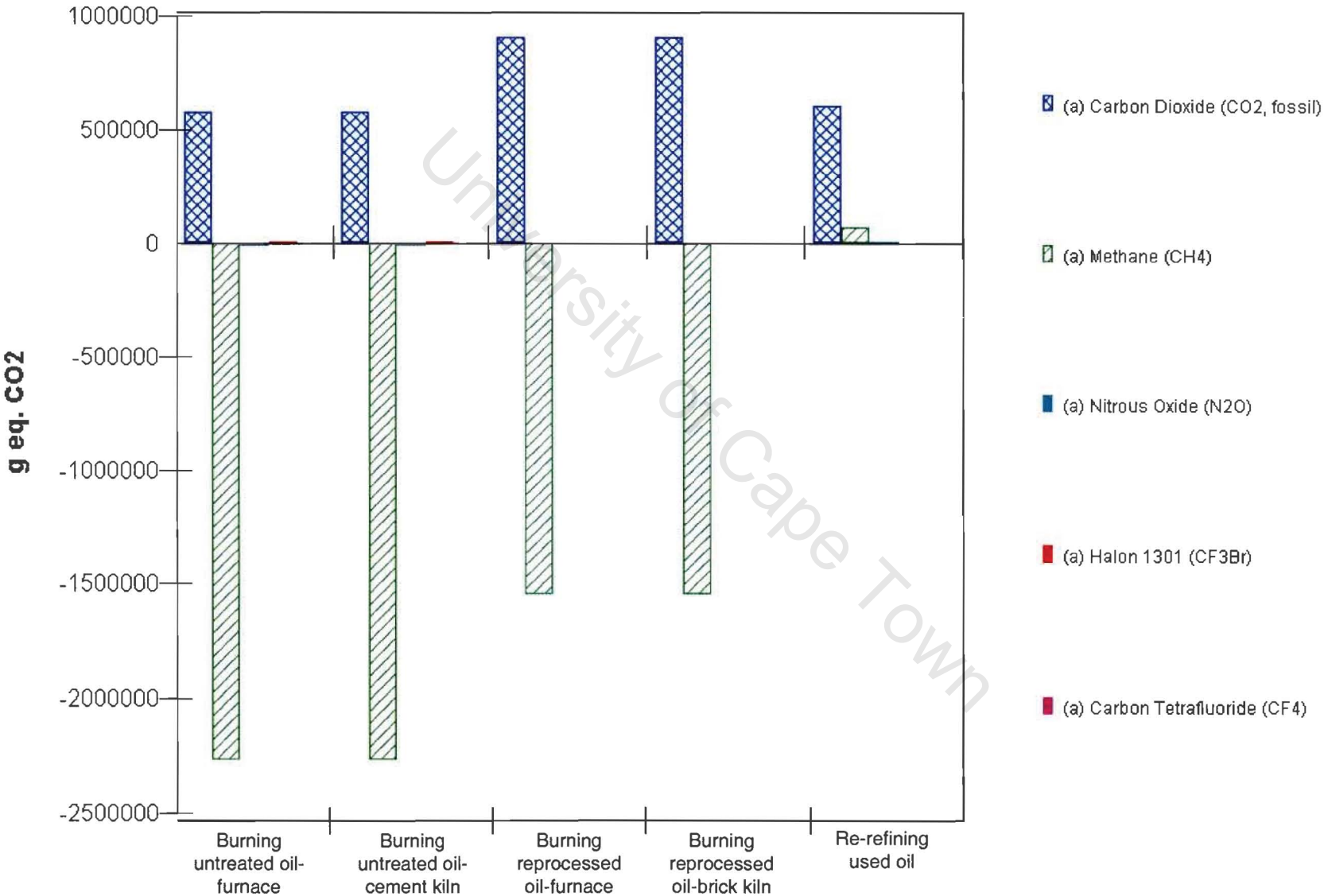


Figure 8.6 IPCC-Greenhouse Effect (direct, 20 yrs)potentials for selected used oil management scenarios

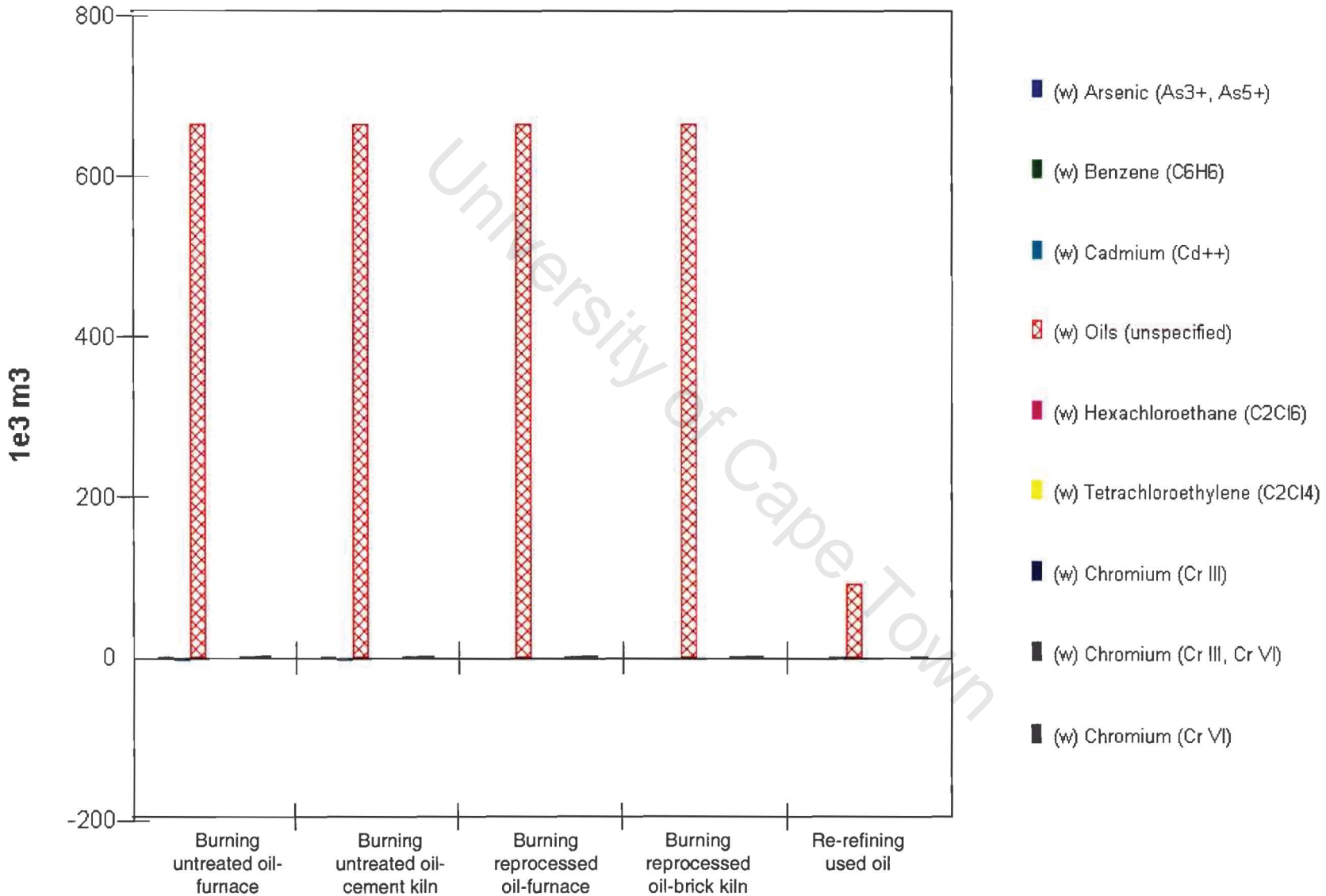


Figure 8.7 CML-Aquatic Ecotoxicity Toxicity potentials for selected used oil management scenarios

8.3 COMPARING THE OVERALL ENVIRONMENTAL PERFORMANCE OF SELECTED USED OIL MANAGEMENT SCENARIOS BASED ON LCIA

Figure 8.8 shows the LCIA results presented for each impact category rationalised as a fraction of the highest impact value for the used oil management scenarios which is given a value of 1 and the lowest impact value being given a value of minus 1 (-1). For example, the LCIA results showing the potential contributions to human toxicity given in Figure 8.1 show that the scenario in which untreated used oil is burned in industrial furnaces presents the highest potential to human toxicity. In Figure 8.8 this highest toxicity potential is given a value of 1, and the human toxicity potentials of the other management scenarios are taken as positive or negative fractions of this highest value. The rationalised negative impact values reflect the gains to the environment for the used oil burning scenarios resulting from quantitatively greater avoided impacts of HFO production and combustion.

The results of comparing the overall performance of the selected used oil management scenarios based on the rationalised LCIA category values, assuming that all the life cycle impact categories have equal relative importance, show the selected scenarios present variable performance for the LCIA categories used in the assessment. The results also show that both re-refining and the energetic use scenarios present the best environmental performance for different impact categories with re-refining offering the best performance on aquatic ecotoxicity, eutrophication and photochemical oxidant formation potentials. The energetic use scenarios give the best performance of the remaining 3 LCIA categories with the scenarios in which used oil is burned without prior treatment showing the lowest potential for causing the greenhouse effect. The burning of untreated oil in industrial furnaces would result in the lowest releases of substances causing air acidification and the scenario in which reprocessed oil is burned in industrial furnaces releases the lowest amount of substances attributed to negative human health effects.

It would be difficult to present one management scenario which could be said to offer the best overall environmental performance based on the results of the LCIA. A distinction of the overall performance of one management scenario would have to be based on giving variable importance to the impact categories used in the assessment.

The difficulty in determining the best performing option in a comparative analysis is recognised and ISO 14042 (2000), the standard giving guidelines on LCIA recommends that this be done in conjunction with other considerations. For this reason the best performing used oil management scenarios will be proposed in Chapter 9, with the consideration of the life cycle inventory assessment results as well as other logistical considerations that have to be considered in used oil management in South Africa

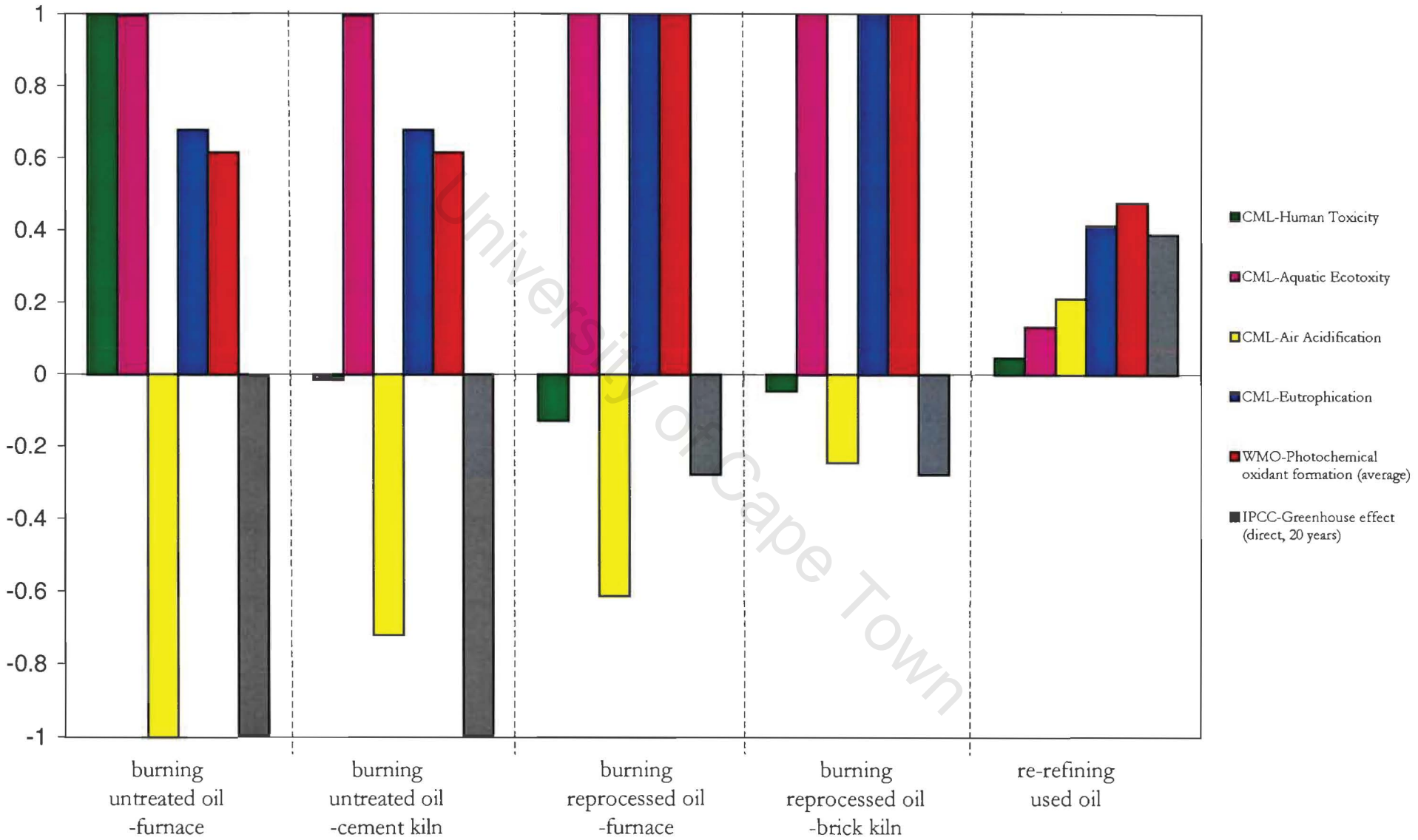


Figure 8.8 Assessment of the overall environmental performance of selected used oil management scenarios based on rationalised LCIA results

8.4 CONCLUSION

The assessment of the used oil management scenarios based on the selected LCIA categories reveals differences in environmental performance and identifies areas of improvement.

If it is assumed that the LCIA categories used in the study are of equal importance in South Africa then the used oil management scenarios in which used lubricating oil is re-refined and the scenario in which used oil is burned as a fuel in cement kilns have to be considered as showing the best environmental performance in South Africa. The selection of one superior management option would have to be made with consideration of other factors.

When comparing the results of the LCIA based assessment to the results of the life cycle inventory flow based assessment presented in Chapter 7 similarities are found for impact categories where an inventory flow is a dominant contributor to the respective impact category. This is clearly illustrated by considering the results of the inventory flow comparisons based on lead emissions ((a) Lead (Pb)) and oils in wastewater ((w) Oils (unspecified)) (see Table 7.2, Figure 7.3) and the respective LCIA results for human toxicity and aquatic ecotoxicity (see Figure 8.1, 8.2 and 8.7)

As in the assessment of used oil management scenarios based on inventory flows, the results generated for the used oil management scenarios, potential for contributing to eutrophication, photochemical oxidant formation and the greenhouse effect are strongly influenced by the consequences posed by re-refining on the refinery operations as well as the benefits derived from avoiding the impacts of HFO production and combustion when used oil burning scenarios are considered.

The assessment methods used in presenting results in Chapter 7 and Chapter 8 will be used in Chapter 9 in verifying the hypotheses presented for the study and for making recommendations for the future use of the model to inform used oil management in South Africa.

Chapter 9

Conclusions and Recommendations

An LCA based model that can be used to investigate and evaluate the environmental performance of specific scenarios for used oil management in South Africa was developed. Data, generally of first-order accuracy and applicability, was collected for use in the model. Within the restrictions of the data quality, the model was used to investigate the performance of hypothetical used oil management scenarios in which the entire volume of collected used oil is routed to one of the following management options:

- Burning of untreated used oil in industrial furnaces,
- Burning of untreated used oil in cement kilns,
- Burning of reprocessed oil in industrial furnaces,
- Burning of reprocessed oil in brick kilns,
- Re-refining of used oil using the Revivoil Re-refining process.

The environmental performance of the selected scenarios was assessed based on two methods;

- using the results generated by the model for a selected number of inventory flows which are considered to be important environmental performance indicators in South Africa,
- using Life Cycle Impact Assessment (LCIA) categories.

The results generated from this model can be used to inform on a broad based strategy for used oil management by assessing the environmental benefits of selected scenarios within the context of the entire lube oil manufacturing, use and re-use system thereby identifying opportunities for improvement. However, before conclusions and recommendations are presented, the factors which influence the context in which the results are interpreted will be summarised. These relate to; model structure, model focus, model uncertainty and data quality.

8.1 Model Structure: Choice of System Boundaries

In the study as well as in the model all elements or processing sub-systems common to all the management scenarios were placed outside the system boundaries. The elements put within the system boundaries are crude oil extraction, sections of the fuels refinery and base oil plant systems, and the recycling systems in which the used oil is processed. Elements common to the management scenarios that were placed outside the system boundaries are additive production and distribution, the lubricating oil blending and distribution, lube oil losses during use, used oil collection and storage systems, and the processing of refinery products other than lubricating oils.

This choice of system boundaries is only applicable with the following conditions, and the results should be interpreted within the context of these conditions being applicable:

- The re-refined base oil recycled into the use system is blended with the same additives, produced and distributed through the same processes as virgin base oils,
- The losses during lubricating oil use have the same impact regardless of the management scenario under consideration,
- The collection and storage systems have equal burdens regardless of the management scenario under consideration. This condition is based on the assumption that the environmental burdens associated with the truck transport of collected oil to use scenarios

are taken to be equal regardless of the scenario considered. This assumption was made because the management scenarios in the study were not assigned specific locations and it would be difficult to assign transport data. However, in future use of the model, where site-specific end-use scenarios are considered, the burdens associated with transport could be incorporated.

In placing of the processing of other refinery products outside the assessment boundaries assumptions regarding the flows in the fuels refinery were made. It was proposed that the recycling of re-refined base oils, although influencing the scale of operation of the base oil refinery plant, would not result in a decrease in the quantity of crude oil processed in the refinery system, but rather an increase in the quantity of other refinery products produced. The assumed relationship would only influence the allocation of environmental burdens incurred in crude oil extraction, transport, storage and the first processing steps-distillation.

The environmental impacts to the broader refinery system that would arise from recycling base oil would be quantified as the marginal difference between the reduction of burdens that is gained from decreasing the quantity of refinery product treated in the base oil refinery and the increased burdens resulting from the increased quantity of intermediate products that would be processed to other refinery products. The latter would however be allocated to other petroleum products and was not of concern in this study.

In interpreting the results of the study one must be cognisant that the selected choice of system boundaries imply that the improvements that are presented form the results are valid within the context of the selected boundaries. The process of quantifying the benefits of re-refining based on the environmental changes that would be effected by the increased production of other refinery products would require an assessment of the entire fuels refinery system.

9.2 Model Focus: The Choice of Fuel Substituted by Used Oil in Energetic Use Scenarios

The results of the assessment of energetic use scenarios reveals that their potential for improving the system environmental performance is derived from avoiding the impacts that would be associated with the production and utilisation of the fuel they would substitute in a given application. In the study it was assumed that used oil and its products would substitute heavy fuel oil (HFO) in respective industrial applications. This assumption therefore implies that the environmental improvements associated with an energetic use scenario are specifically derived from avoiding the impacts of HFO production and combustion.

The results of this study should therefore be interpreted specifically within the context of assessing the benefits of the energetic use scenarios in as far as they avoid the impacts of HFO production and combustion. These results cannot and should not be extrapolated to systems where the used oil or its fuel products would be substituting other fuels, such as coal.

The assessment of the benefits that would be gained from used oil or its fuel products being used as a substitute for coal in industrial applications would require that life cycle inventory data be gathered for coal production, and coal combustion in the respective industrial application. It is noted that the developed model would be amenable to such a change in focus.

9.3 Structural Uncertainty in the Model: Allocation of Burdens in the Refineries System

The environmental burdens associated with the base oil refinery plant were allocated using an assumed economic value of 80%. This assumed economic value was not arbitrarily selected but was selected based on considerations of the refinery system's product mass to gross revenue relationships (SAPREF, 1999). The sensitivity of the results to the assumed allocation showed that the trends in environmental performance of the selected used oil management scenarios

would not be significantly affected 15 percentage point changes around the assumed value. However, for purposes of presenting results on which broad consensus can be reached it is recommended that data be collected for determining accurate allocation relationships.

9.4 Data Quality Issues

Important data quality considerations when interpreting the results of the study concern; the applicability and accuracy of data incorporated into the model from software data bases, the quality of data sourced from publications and the completeness and accuracy of data gathered in the field.

In the first regard an important consideration is the use of DEAM™ data module for HFO production and combustion, a consideration identified as an important factor in assessing the performance of the selected scenarios. This module represents averaged European data and was modified for key South African data points for utilities provision (steam consumption, fuel energy use, total water use and electricity consumption) as well as for sulphur oxides emissions. Other data contained in the module was assumed to be representative of the South African system. However, the results of the life cycle impact assessment showed uncharacteristically high methane (CH_4) emissions only in the HFO production and combustion system. This was considered to be an error possibly having arisen during the module construction process. This possible anomaly in the data module highlights the need for detailed emissions data to be made available for the HFO production system, and well as the broader refinery system in South Africa to increase the confidence in the results.

The results were also affected by the quality of data presented in published articles. This is illustrated by considering the influence of the documented large make-up water requirements of the Revivoil reprocessing and re-refining systems considered in the study on the overall water use performance of the management scenarios. In addition, data available for the Revivoil Processes, although detailed, did not include data on fugitive emissions of potentially toxic light hydrocarbons, aromatics, solvents and any other compounds that are typically emitted from refinery processes.

The data modules in the model were also built from data collected in the field. Modules for the refinery system were compiled from day to day process data as well as from detailed surveys such as the Solomon's Study. Data from the refinery operations, as with the published data for the re-refining process, did not include fugitive emissions of compounds such as light hydrocarbons, aromatics, solvents from the base oil plant and other emissions that could be released from the processing of oils. In addition, data for the fuels refinery effluent was not provided and it was assumed that the effluent composition could be represented by maximum permissible contaminants concentrations as stipulated by the Water Act and the Durban City drainage by-laws.

These examples of areas where there is missing or inaccurate data show that there is scope for improving the model by improving data completeness and verifying assumptions and accuracy issues that influence the data quality.

9.5 Differences in Performance Revealed from the LCA Study

The comparative analysis of the selected used oil management scenarios was based on the results from the life cycle impact assessment (LCIA) and on an interpretation of selected inventory flows as environmental performance indicators. Both methods revealed significant differences in performance. These will be categorised and discussed as differences in performance between re-refining and the energetic use scenarios, and the differences in performance amongst the energetic use scenarios.

9.5.1 Comparing re-refining to energetic use scenarios

The inventory results showed that the re-refining scenario presented superior environmental performance to the energetic use scenarios for some of the burdens considered explicitly, whilst the inverse was true for others. It is thus not surprising to note that the re-refining scenario presents superior performance to the energetic use scenarios for some of the LCIA impact categories while the energetic use scenarios shows superior performance in others.

Re-refining offers good environmental performance when considered for its low used oil contaminants emissions as illustrated from the lead emissions results presented in the study. Because re-refining has the potential to influence the scale of operations of the base oil refining system it has resultant benefits from reduced fuel energy demands and nitrogen oxides emissions for which it presents the best performance from an inventory flow assessment perspective. Re-refining also presents the best environmental performance when assessed for its potential contributions to the impact categories of aquatic ecotoxicity, eutrophication and photochemical oxidant formation.

9.5.2 Comparing the energetic use scenarios

The LCIA and inventory results based analyses of the energetic use scenarios revealed that their potential for environmental improvement would be derived from substituting HFO as fuel in respective industrial applications, thereby avoiding quantified environmental impacts associated with HFO production and combustion. It must be recognised that even though there are difference in the performance of the energetic use scenarios each of the scenarios presented some gain for the environment by substituting the burning of HFO.

An exception to this generally recognised improvement from substituting HFO as a fuel is when considering the burning of untreated used oil in industrial furnaces. The burning of untreated used oil in industrial furnaces, although presenting significant environmental benefits derived from avoided processing utility and environmental burdens, releases virtually all the metallic contaminants in the used oil through the stack. The emission of metallic contaminants in used oil, particularly lead may contribute to negative human health effects. This effect is illustrated from considering the relatively high human toxicity potentials determined in LCIA for the burning of untreated used oil in industrial furnaces. Based on this recognition it is recommended that all used oils be treated before use or be disposed in an application in which the used oil contaminants are arrested.

The energetic scenarios in which reprocessed oil is burned significantly reduce the human toxicity potentials associated with the burning of used oil as the contaminants are largely removed from the final fuel product that is burned. However, the reprocessing plants have associated utility requirements and environmental burdens. In addition to this reprocessing produces a smaller quantity of fuel product hence reducing the potential benefits that could be derived from avoiding the impacts of HFO production and combustion. The results of the LCIA for the management options showed that the reprocessing options had highest potential for contributing to three of the six impact categories considered in the assessment, which are aquatic ecotoxicity, eutrophication and photochemical oxidant formation. There is potential for improving the performance of the reprocessing options through efficient utilities use, especially water and fuel energy use, as well as the improvement in the environmental performance of associated life cycle sub-stages.

Of the energetic use scenarios the burning of untreated used oil in cement kilns presents the widest scope for environmental performance improvement when considered both from an inventory flow and an LCIA perspective. The burning of used oil in cement kilns presents the largest marginal benefits from the avoided impacts of HFO production and combustion in the categories of water use and the release of chemically polluted effluent. In cement kilns most of the contaminants in used oils either react with the raw meal feed or trapped in the cement

product matrix. The LCIA results also show that the burning of untreated oil in cement kilns with the use of pollution abatement systems could have even lower potential for contributing to negative human health effects. The burning of used oil in cement kilns would also result in the largest environmental gains from reducing the release of substances that cause air acidification and contribute to the greenhouse effect, the latter being subject to accuracy of CH_4 emissions data as discussed earlier.

9.5.3 Determining the overall performance of the scenarios

The findings from the study show that both re-refining and the energetic use scenarios present opportunities for environmental improvement for different performance indicators considered in the study. The energetic use scenarios would yield improvements from the avoided impacts of HFO production and combustion, while re-refining would reduce the burdens associated with base oil production. Each of the management scenarios also showed variable performance from the inventory flow and the LCIA based analyses. Rather than identifying a single management option that may be considered as presenting the best overall performance in the South African context, the results of the study showed the performance of each scenario and identified performance areas needing improvements if the scenario were to be considered. It is also recommended that in assessing the performance of the scenarios other factors be considered. Such factors for choosing between management options could be:

- The assigning of different importance factors (weighting factors) to the LCIA categories and inventory flow results. For example, if human toxicity is given the highest relative importance then the burning of used oil in systems that prevent the release of substances affecting human health such as the burning of reprocessed oils would become more desirable.

- Currently used oils are re-refined in South Africa using the acid clay treatment process, a first-generation treatment method with unacceptable environmental consequences. A new re-refining plant would have to be commissioned and its environmental performance would have to be assessed. Issues pertaining to the capacity of the re-refining plant, its location and whether one or more should be built in the various provinces would have to be considered. The successful operation of a re-refining plant would also depend on the guaranteed availability of used oils feed for the capacity of the re-refining plant as well as the availability of a market for the product. Re-refined oils also have to meet stringent performance standards that are specified for virgin base oils.

- The environmental performance of local reprocessing operations as well as cement kilns would have to be assessed from experimental and process analyses of the respective operations. In the study data for the burning of used oil in cement kilns was based on experimental work carried out in Canada. The performance of local operations would have to be assessed for individual cement producing operation before final recommendations on burning used oils in the kilns can be made.

- The selection of a given scenario for used oil management would also be influenced by the logistics of collecting and delivering used oil to location of the processing site for a respective scenario.

9.6 Verifying the Hypotheses Presented for the Study

An interpretation of life cycle inventory (LCI) and life cycle impact assessment (LCIA) results obtained for the first-order assessment revealed significant differences in performance for the selected management scenarios. The results show that the energetic use scenarios have potential for improving environmental performance when Heavy Fuel Oil (HFO) is substituted by used oil in energy utilities, thereby avoiding the environmental impacts associated with HFO production

and combustion. The results also revealed the sub-systems having the most significant contributions to the performance of a scenario. In particular the results showed that the potential for causing damage to aquatic systems would be significantly reduced by reducing the quantity of oils released into water systems at the base oil refinery plants. The results also showed that the water demands of a re-refining or reprocessing operation would affect the performance on the scenario from a life cycle perspective. In addition to this the results of the assessment showed that a used oil management scenario's potential to cause negative human health effects is significantly affected by the extent of emission of the metallic contaminants in the oil at the recycling stage on the scenario. The results generated from the model therefore support the first hypothesis presented for the study which stated;

"Comparative Life Cycle Assessment of the available used oil management and technology options will reveal significant differences in environmental performance and will serve to identify areas of improvement."

It may further be concluded from the study that both re-refining and the energetic use scenarios show variable performance when assessed using the LCIA and analysed used inventory flows. No single management option can be considered as giving a comprehensively superior performance for the environmental indicators considered in the study. It is therefore recommended that other factors be considered in for determining the route to be taken in managing used lubricating oils in South Africa. These findings therefore disprove the second hypothesis presented for the study, that re-refining would offer the best environmental performance being transcendent of the benefits that would be yielded by the energetic use scenarios.

9.7 Recommendations for Further Use of the Model and Future Studies

Based on the findings of the study the following recommendations for improving the model and for future study can be made:

- The computational model developed and used in the assessment is based on first-order data and there is scope for improving data quality for certain stages of the system life cycle. The avoided impacts of HFO production and combustion have been found to be a dominant factor in influencing the performance of the energetic use scenarios. Data for HFO production and combustion was however based on a European production data module which was adjusted to reflect the utility flows associated with the production of HFO in South Africa. The model could be made more robust by carrying out a detailed analysis of HFO production in South Africa and in particular effluent and emissions data should be made available by refineries if more accurate results for the LCA are desired.

- Local reprocessing operations were not considered in the study and there is scope to build extensive data inventories for their operations. This data would be incorporated into the model thus allowing their comparison to internationally marketed reprocessing units as well as to other used oil management scenarios.

- The burning of used oil in cement kilns presents the most readily implementable environmentally sound solution to used oil management. However experimental work has to be carried out at the chosen cement making operations to determine their performance with regards to very specific issues such as the extent of retention of metal contaminants in the oil, the extent of retention of sulphur compounds, the efficiency of pollution abatement equipment and the fate of solid wastes derived from the process.

- The model has presented and evaluated the performance of energetic use scenarios as relative to the avoided impacts of HFO production and combustion. The model is however

amenable to considering other fuel substitution options such as coal, electricity and fuel gas. There is therefore scope for further work to compare the performance of used oil fuels as a substitute particularly to coal in selected industrial applications, involving the building of coal production and combustion inventories in South Africa.

- As already discussed re-refining in South Africa is carried out using the first generation acid clay treatment process, and there is scope for introducing a modern technology. The model could be used in assessing the performance of various re-refining technologies so as to identify areas of improvement before commissioning in South Africa.

- The use of the model in the comparative analysis of selected management scenarios shows differences in performance and also reveals opportunities for improvement. The model has thus proved to be successful as a tool for comparing alternative scenarios and options for managing used oils in South Africa. Future work with the model should focus on improving the accuracy and representativeness of its results through the collection of missing data as well as the incorporation of site specific scenario assessments of local recycling operations such as cement kilns, reprocessing plants and new re-refining technologies being considered.

References

ADEME (2000) Recyclage et volarisation energetique des huiles usages, Atout et Faiblesses, Direction de L'Industrie, ADEME Cetre d'Angers, ADEME Editions, Angers.

Al-Ahmad, M.I. and Al-Mutaz, I.S. (1991) Techno-economic study of Re-refining Waste Lubricating Oils in the Arabian Gulf Countries. *Resources, Conservation and Recycling* **6**, 71-78.

Allen, J.L. (1976) Evaluating a Waste Oil Reclamation System. *Plant Engineering* **30**, 255-256.

Arner, R. (1989) Used Oil Recycling: State and Local Collection Programs. *Resource recycling* **8**, 22-23,72,75.

Arner, R. (1991) Curbside Recycling of Used Oil. *Resource recycling* **10**, 100-105

Arner, R. (1996) Checking the Oil Recovery System. *Biocycle* **37**, 69-70.

Alves dos Reis, M. (1991) Waste Lubricating Oil Re-refining by Extraction-Flocculation. 3. A Pilot Plant Study. *Ind. Eng. Chem. Res.* **30**, 2449-2456.

Alves dos Reis, M. and Silva Jeronimo, M. (1988) Waste Lubricating Oil Re-refining by Extraction-Flocculation. 1. A Scientific Basis To Design Efficient Solvents. *Ind. Eng. Chem. Res.* **28**, 1222-1228.

Alves dos Reis, M. and Silva Jeronimo, M. (1990) Waste Lubricating Oil Re-refining by Extraction-Flocculation. 2. A Method to Formulate Efficient Composite Solvents. *Ind. Eng. Chem. Res.* **29**, 432-436.

Azapagic, A., Solberg-Johansen, B. (1998) Life Cycle Assessment, *Engineering* **239**, 26-28.

Azapagic, A., Clift, R., (1999) Life Cycle Assessment and Multiobjective Optimisation, *J. of Cleaner Production* **7**, 135 – 143

[1]Ball, J.S., Thompson, C.J. and Whisman, M.L. (1977) Used Oil Processing Research at the US Department of Enegy, Bartlesvilee Energy Research Centre. Used Oil Re-Refining Hearing Before the Subcommittee on advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

[6]Ball, J.S., Thompson, C.J. and Whisman, M.L. (1977)pp 82-83, Used Oil Processing Research at the US Department of Enegy, Bartlesvilee Energy Research Centre. Used Oil Re-Refining Hearing Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

Basu, P., Kefa, Cen., Jesten, L., Boilers and Burners Design and Theory, Mechanical Engineering Series Springer-Verlag New York, Inc. 2000

Becker, D.A. and Comeford, J.J. (1980) *Used Oil Recycling Joint Hearing* Before the Subcommittee on Energy and Power and the Subcommittee on Transport and Commerce of the Committee on Interstate and Foreign Commerce, House of Representatives, 96th Congress, 2nd Session, H.R. 7833 and S. 2412, Serial No. 96-199, Government Printing Office.

Beiring, E.A. (1993) Used Oil in the United States: Environmental Impact, Regulation and Management. *Buffalo Law Review* 41, 157-202.

Berry, E. E., MacDonald, L.P., Skinner, D. J. (1975) *Experimental Burning of Waste Oil As A Fuel in Cement Manufacture*, Report No. EPS 4-WP-75-1

Bhan, O.K., Tai, W.P. and Brinkman, D.W. (1986) Hydrotreat Used Lube Oil. *Hydrocarbon Processing* 67-68.

Billon, A., Cohen, G., Schieppati, R.. (1995) Quality Improvement of the Re-refined Base Oils by IFP/Viscolube Waste Oil Technolgy, Seminario Basi Minerali Riraffinate: Valenze Ambientale e Tecniche, Torino.

Blendcor Effluent Report Reference No 286/00/B, 2000, Echalaz and Osborne (Pty) Ltd, Consulting Industrial and Marine Chemists, Commodity Inspectors, Samplers and Surveyors.

Bowen, T. (1980) Status of the MIL-L-46152A Engine Oil Specification, *Joint Conference on Measurements and Standards for Recycled Oil/Systems Performance and Durability*, pp 51-54, Proceedings of a Conference held at the National Bureau of Standards, Gaithersburg. Donald A. Becker, Editor.

Boustead Consulting Ltd, (1998) ISO 14042 Life Cycle Assessment – Life Cycle Impact Assessment, http://www.boustead-consulting.co.uk/impactas.htm (last modified Oct. 1998)

BP Laboratory Report, (1984) Lab. Report No. 84/293, Analysis No. B/84/180, Residue for Stack Ex HFO De Hoop Bricks, BP Southern Southern Africa (Pty) Ltd.

Brinkman, D.W. (1986) Used Oil:Resource or Pollutant? *CHEMTECH*, 682-684.

Brinkman, D.W. (1987) Technologies for Re-Refining Used Lubricating Oils. *Lubrication Engineering* 43, 324-328.

Brinkman, D.W. (1991) Large Grassroots Lube Re-refinery in Operation. *Oil and Gas Journal* 60-63.

Brinkman, D.W. and Dickson, J. R. (1995) Contaminants in Used Lubricating Oils and their Fate during Distillation/Hydrotreatment Re-refining. *Environmental Science and Technology* **29**, 81-86.

British Petroleum Company Ltd. (BP), *Industrial Lubrication*, Appendix. pp 308 –314, W. & J. Jarvis Limited, 1966.

Cabrita, I., Lopes, H. and Gulyurtlu, I. (1996) The Determination of Pollutants from Burning Waste Oils. *Fuel* **75**, 940-944.

Cairncross, E.K., and Manuel, G. (1999) A Preliminary Source-Receptor Model of Industrial Emissions from the Sacks Circle, Bellville Industrial Area, Department of Physical Science, Peninsula Technikon, Bellville, South Africa.

Cairncross, E.K., and Manuel, G. (2000) Research Data: Stack emissions data, Sacks Circle, Bellville, South Africa

Caltex Refinery, Cape Town. 1981 Industrial Study Tour. Prepared by Technical Services Department

[1]CCME Report No CCNE_TS/WM_TRE007, (1989) pp 65, Canadian Council of Ministers of the Environment, *Used Oil Management in Canada: Existing Practices and Alternatives*, by Monenco Consultants Ltd.

[2]CCME Report No CCNE_TS/WM_TRE007, (1989) pp xvi, Canadian Council of Ministers of the Environment, *Used Oil Management in Canada: Existing Practices and Alternatives*, by Monenco Consultants Ltd.

[3]CCME Report No CCNE_TS/WM_TRE007, (1989) pp 72-80, Canadian Council of Ministers of the Environment, *Used Oil Management in Canada: Existing Practices and Alternatives*, by Monenco Consultants Ltd.

[4]CCME Report No CCNE_TS/WM_TRE007, (1989) pp 49-71, Canadian Council of Ministers of the Environment, *Used Oil Management in Canada: Existing Practices and Alternatives*, by Monenco Consultants Ltd.

[5]CCME Report No CCNE_TS/WM_TRE007, (1989) pp 51, Canadian Council of Ministers of the Environment, *Used Oil Management in Canada: Existing Practices and Alternatives*, by Monenco Consultants Ltd.

[6]CCME Report No CCNE_TS/WM_TRE007, (1989) pp 52, Canadian Council of Ministers of the Environment, *Used Oil Management in Canada: Existing Practices and Alternatives*, by Monenco Consultants Ltd.

Chatwin, A.H. (1975) The Re-Refining of Used Lubricating Oils. *Petroleum Review* 29, 713-716.

Chiogioji, M.H. (1974) Waste Oil: A Resource to be Conserved. 740684, United States: Society of Automotive Engineers.

Christiansen, K., in Wiedema, B.P., Chapter 1, 1993

Ciambrone, D.F., Environmental Life Cycle Analysis, Lewis Publishers, CRC Press 1997.

CML, (2000) Centre of Environmental Science, Substances and Products Section, http://www.leidenuniv.nl/interfac/cml/ssp/gisp/html

Coghill, D. (1998) The Effect on Centrifuge Performance of the Addition of Used Lubricating Oil in Residual Fuel- Results of a Joint Study between BP Marine and Alfa Laval, 19th International Bunker Conference, London U.K.

CONCAWE Report No. 5/96 (1996) Collection and Disposal of Used Lubricating Oil.

Consoli, F.J. (1995) Life Cycle Assessment: Background and Update, *Tappi Journal* 78 No. 12, 41-43

Cox Industries, Inc. (1999) http://www.coxwood.com

Curran, M.A. (1993) Broad-based Environmental Life Cycle Assessment, *Environ. Sci. Technol.* 27 No 3. 430-436.

Davies, J.P. (1996) The Interline Process for Re-refining of Used Lubricating Oils, Technical Memorandum, BP France Confidential Branch Report No: 1356-JP.D

Davies, J.P. (2000) Used Lubricating Oil Disposal Update, personal communication to Norton, S. Chief Executive, Rose Foundation, Republic of South Africa

De Hoop Bricks Report, (1995) Report on Stack Emission Measurements at De Hoop Bricks, Paarl, C & M Consulting Engineers, Air Pollution Consultants, Lynnwood Ridge 0040, Pretoria, South Africa.

Department Of Water Affairs, South Africa, (1999) Specification for Effluents (Maximum permissible Concentrations)

Diab, A. and Barnard, J.P. (1999) Non-linear Time Series Analysis: An Approach to Modelling NOx Concentrations, National Association for Clean Air (NACA), Annual Clean Air Conference, Cape Town

Diab, R.D. and Matooane, L. (1999) Air Pollution Carrying Capacity in the South Durban Industrial Basin, National Association for Clean Air (NACA), Annual Clean Air Conference, Cape Town

Doerffer, J.W., Oil Spill Response in the Marine Environment, Pergamon Press Ltd., 1992.

Domenici, P.V. (1981) A Boost for Waste Oil Recycling. *Catalyst* 7, 18-21.

Ecobilan Website (2000) http://www.ecobalance.com/software/team/team_tech.html

Engen Lube Oil Blend Plant Report, (1999) Physical Plant Overview
FFS Refineries (Pty) Ltd., Company Profile Brochure, ffs@ffs.co.za

ENI (2000) http://www.eni.it

Forbes, P.B.C. (1999) The use of Life Cycle Assessment in the Evaluation of Environmental Performance in the Base Metal Refining Industry, Dissertation submitted to the University of Cape Town in fulfilment of the requirements for the degree of Master of Science of Applied Science.

Graedel, T.E., Streamlined Life-Cycle Assessment, Bell Laboratories, Lucent Technologies, Prentice Hall, Inc. 1998.

Giddens, J. (1976) Spent Motor Oil Effects on Soil and Crops. *J. Environ.. Qual.* 5, 179-181.

Giovanna, D.F., Tromeur, P., Cohen, G. (1999) Viscolube-IFP Revivoil: Sucessful Re-refining in Practice. *Used Oil Management Conference*, Parkroyal Hotel, Surfers Paradise, Gold Coast, Australia.

Hakes, S., Craven, J., Duncan, J. and Wulf, B. (1997) California's Used Oil Collection and Recycling Program, *Solid Waste Association of North America Waste Conference 35 Annual International Solid Waste Expo,* St. Loius, Mo.

Hauschild, M., Wenzel, H., Environmental Assessment of Products, Volume 2 Scientific Background, Institute for Product Development, Chapman and Hall, 1998.

Hockley, C.G. and Walters, J. (1989) An Oil Resource that No-one Wants. *Opec Bulletin* 20, 15-18.

Holloway, T. (1992) Life Cycle Assessment – A New Yardstick?, *Process Engineering* 73, 19-21

Hsu, S.M. (1980) Engine Oil Evaluation Through Bench Testing, *Joint Conference on Measurements and Standards for Recycled Oil/Systems Performance and Durability,* pp 191-204, Proceedings of a Conference held at the National Bureau of Standards, Gaithersburg. Donald A. Becker, Editor.

Iaquaniello, G., Vinci, F. and D'Arco, A. (1989) Rotary Kiln Incineration Control Strategies. *Hydrocarbon Processing,* 39-42.

International Standards Organisation, ISO 14041:1998(E) , ISO/TC 207 SC 5, Final Draft - Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis

ISO 14042 (2000) International Standard Organisation, International Standard: Environmental Management-Life Cycle Assessment-Life Cycle Impact Assessment
ISO 14043 (2000) International Standards Organisation, International Standard: Environmental Management-Life Cycle Assessment-Life Cycle Interpretation

Irwin, W.A. (1978) Used Oil: Collection, Recycling and Disposal. *Technology Review* 80, 54-61.

IPCC (2000) Intergovernmental Panel for Climate Change, http://www.ipcc.ch/about/about.htm

J. Muller Laboratory Reports (1999) J. Muller Laboratories (Pty) Ltd., Analytical Chemists, P.O. Box 511, Paarden Eiland 7420, South Africa

Jacobs, M. (1977) Recycling Oil: a Question of Quality. *Dimensions: National Bureau of Standards* 61, 8-13.

Jonson, G. (1996) LCA – A tool for Measuring Environmental Performance, Pira, UK, 50-53

Kachler, R. (1980) The Recycling of Used Oils in France, *CEC Recycling of Used Oils 2nd Symposium,* Paris.

Kalnes, T.N., Youtsey, K.J., James, R.B., Hedden, D.R. (1989) Recycling Waste Lube Oils for Profit (UOP Direct Contact Hydrogenation Process). *Hazardous Waste and Hazardous Materials* 6, 51-66.

Kazan, S.Esq. (2000) Kazan, McLain, Edises, Simon & Abrams Law Corporation, http://www.kazanlaw.com/otherpractice/symptoms.shtml

Kerran, M.L. (1977) *Used Oil Re-Refining Hearing* Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

Knotse, H. (1994) Thermochemical Calculations for Combustion Products at Dehoop Bricks, Paarl, Stellenbosch University, South Africa.

Krewitt, W., Mayerhofer, P., Trukenmuller, A., Friedrich, R. (1998) LCA Methodology: Application of the Impact Pathway Analysis in the Context of LCA, The Long Way from Burden to Impact, *Int. J. LCA*. 3 No 2, 86-94.

Kroop, H., Lieberman, M. and Beerbower, A. (1974) Disposal of Waste Oils at Millitary Air Bases. *Society of Automotive Engineers* 72, 1-5.

Krozer, J. and Vis, J.C. (1998) How to get LCA in the right direction?, Journal of Cleaner Production 6 pp 53-61

Kuhre, W.L., ISO 14001 Certification, Environmental Management Systems – A Practical Guide for Preparing Effective Management Systems, Prentice Hall PTR, 1995.

Lecouls, H., (1999) ISO 14043: Environmental Management-Life Cycle Assessment-Life Cycle Iterpretation, International Journal of LCA, 4 (2) pp 81-86.

Lee, F. and Gentry, J.C. (1997) Don't Overlook Extractive Distillation. *Chem. Eng. Prog.* 56-64.

Linde, H. (1999) Air Pollution in the Cape Metropolitan Area-1960s to 2000s, National Association for Clean Air (NACA), Annual Clean Air Conference, Cape Town

[1]Linnard, R.D. (1977) *Used Motor Oil Re-refining.* pp 124-130, Used Oil Re-Refining Hearing Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

Lohof, A. (1991a) Where Has All The Used Oil Gone? Where can it Go? *International Environmental Affairs* 3, 259-281.

Lohof, A. (1991b) Used Oil Management in Selected Industrialised Countries., *Resource Recycling* 10, 62-66

Lubrizol Reference Library, (2000) Lubrication Theory and Practise, Http://www.lubrizol.com/referencelibrary/lubetheory/index.htm

Markovic, V., (1998) Future SETAC-Europe LCA Activities, A Personal View, International Journal of LCA, 3 (1) pp 1.

MBendi Information for Africa, (2000) South Africa – Oil and Gas Industry, http://www.mbendi.co.za/indy/oilg/ogrf/af/sa/p0005.htm

McCabe, M. M. and Newton, W. (1997) Waste Oil, Section 4.1 *Standard Handbook for Hazardous Waste Treatment,* Author: Freeman, H.

McEwen Jr, (1976) Re-refining of Waste Lubricating Oil: Federal Perspective. *Resources Recovery and Energy Review* 3, 14-17.

McKeagan, D.J. (1992) Economics of Re-refining Used Lubricants. *Lubrication Engineering* 418-423.

McKendry-Smith, S. (1989) The Cement Kiln Solution. *Bio-joule* 17-21.

Mozes, T. (1997) Technology Review of Options for Reprocessing and Disposal of Used Lubricating Oil, TMC, TM Business Development Consulting, Wierda Park 0149, South Africa.

Mphepya, J. and Held, G. (1999) Dry Deposition of Sulphur on the Mpumalanga Highveld, National Association for Clean Air (NACA), Annual Clean Air Conference, Cape Town.

Muller, K. (1984) Re-refining of Waste Oil, *Chemcontrol A/S 2nd Operating European Hazwaste Management International Symposium,* Odense, Denmark.

Myles, B. (1975) Waste Oil: Untapped Resource. *The Environmental Journal* **49**, 18-19.

Nash, J., Stoughton, M.D. (1994) Learning to Live with Life Cycle Assessment, *Environ. Sci Technol.*, **28** No. 5, 236-237

Neale, M. J. (Editor) *Lubrication: A Tribology Handbook*, pp5-11, Contributor: Fowle, T.L., Butterworth-Heinemann Ltd, 1993.

Norton, S. (1999) Chief Executive, Rose Foundation, Republic of South Africa, (personal communication to Rwodzi, B., UCT Chemical Engineering)

Norton, S. (1999) From the Stone Age to the 21st Century – The Rose Foundation Private Sector Success Story in South Africa, *Used Oil Management Conference*, Parkroyal Hotel, Surfers Paradise, Gold Coast, Australia.

Oliverson, L.R. (1975) Methods and Equipment for Implant Reclamation of Used Lubricants. *Plant Engineering* **29**, 44-47.

Oster, J.A. and Booth Jr, G.T. (1975) A joint Venture of Recycling in Plant Waste Oils. REPORT No. 750388, USA: Society of Automotive Engineers.

Owens, W., (1999) Why Life Cycle Impact Assessment is Now Described as an Indicator System, International Journal of LCA, 4 (2) pp 81-86.

Pearce, D. (1975) The Recovery of Waste Lubricating oil: A Comparative National Analysis. *Resource Policy* 1, 213-229.

Pedall, R.F. (1980) Association of Petroleum Re-refiners Standards for Re-refined Base Oils, *Joint Conference on Measurements and Standards for Recycled Oil/Systems Performance and Durability*, pp 123-125, Proceedings of a Conference held at the National Bureau of Standards, Gaithersburg. Donald A. Becker, Editor.

Pira International, (1995) PEMS.3 User Manual.

Pyziak, T. and Brinkman, D.W. (1993) Recycling and Re-refining of Used Lubricating Oils. *American Society of Lubrication Engineers* **49**, 339-346.

Reindl, J. (1977) Waste Oil Recycling. *Journal of Environmental Health* 40, 52-55.

Rimkus, R.R., Lue-Hing, C. and Lordi, D.T. (1975) Effects of Oil Pollution on Municipal Sewage Treatment Plants, pp 55-56, *2nd international Conference on Waste Oil Recovery and Reuse*, Sheraton Cleveland Hotel, Cleveland, Ohio.

Robinson, E. (1982) Fluidized Bed Combustion of Waste Acid Tars, *CEC Fluidized Bed Systems Contractors Conference*, Brussels (Riedel).

Rose Foundation Data (1998) Lubrizol Survey of Lube Oil Products Sold in South Africa, Rose Foundation, Suite A9, Waverly Court, Kotzee Street, Mowbray 7700, Cape Town, South Africa

Ryding, S., (1999) ISO 14042, Environmental Management-Life Cycle Assessment-Life Cycle Impact Assessment, International Journal of LCA, 4 (6) pp 307.

SABS ISO 14040 (1997) South African Standard, Code of Practice, Environmental Management-Life Cycle Assessment-Principles and Framework, Published by South African Bureau of Standards

SABS ISO 14041 (1998) South African Standard, Code of Practice, Environmental Management-Life Cycle Assessment-Goal and Scope Definition and Inventory Analysis, Published by South African Bureau of Standards

Salusinszky, A. L. (1981) Waste Oil-An Australian Energy Source. *Chemical Engineering in Australia* **6**, 36-39

Sangle, S., Ram Babu, P., Khanna, P. (1999) LCA Methodology: Evaluation of Life Cycle Impacts: Identification of Societal Weights of Environmental Issues, *Int. J. LCA*. **4** No 4, 221-228

SAPREF, Shell and BP South African Petroleum Refineries (Pty) Ltd., SAPREF Product Quality Report, 4th Quarter 1999

SAPREF, Shell and BP South African Petroleum Refineries (Pty) Ltd., (1999), Introduction to Crude Oil Processing, Technical Oil Cooking Course

Schmidt, P.F., Fuel Oil Manual, Industrial Press Inc., New York, 4th Ed 1986

Siemon, D.M., Agnew, J.B. and Szlusinszky, A.L. (1979) Recycling of Used Lubricating Oils in Australia. *Conservation and Recycling* **3**, 25-33.

[1]Sequeira, A. Lubricant Base Oil and Wax Processing, pp 35, Marcel Dekker, Inc, 1st Ed, 1994.

[2]Sequeira, A. Lubricant Base Oil and Wax Processing, pp 120, Marcel Dekker, Inc, 1st Ed, 1994.

Sequeira, A. (1989) Lubricant Base Oil Processing. *Lubrication 75*, No.1, Texaco Inc.

Stachowiak, G.W., Batchelor, A.W. Engineering Tribology, Tribology Series, 24, Elsevier Science Publishers B.V. 1993.

Stumm, W., Morgan., J.J. (1981) Aquatic Chemistry- Introduction Emphasizing Chemical Equilibria in Natural Waters, 2nd Edn. John Wiley and Sons, New York.

Swain Jr, J. W. (1983) Conservation, Recycling and Disposal of Industrial Lubricating Fluids. *Lubrication Engineering* **39**, 551-554.

Tarrer, A.R., Kang, J.H., Kaminski, J., Parrish, J. and Bates, E.R. (1989) Demetallation of Used Oil to Facilitate its Utilisation as a Fuel, pp 123-142, *Hazard Industrial Solid Waste Minimisation Practices (ASTM) Conference Paper.*

Team User's Manual, Version 3.0 Ecobilan Group, 1999

Team Technical Brochure, Ecobilan Group, 1998

Terblanche, P., Nel, R., Opperman, L., Annegarn, H.G., Tosen, G., Cadman, A., Pols, A., Bekker, P. (1994) Triangle Pollution Health Study- final results and recommendations. National Association for Clean Air (NACA) 25th Annual Clean Air Conference, Cape Town

Thompson, C.J. and Brinkman, C.W. (1980) Energy Saving by Re-refining, *CEC Recycling of Used Oil 2nd Symposium*, Paris.

Udo de Haes, H.A. (1993) Applications of Life Cycle Assessment: Expectations, Drawbacks & Perspectives. *J. Cleaner Prod.* **1**, 131-137.

Udo de Haes, H.A. and Jolliet, O., (1999) How Does ISO/DIS 14042 on Life Cycle Impact Assessment Accommodate Current Best Available Practice?, International Journal of LCA, 4 (2) pp 75-80.

Udo de Haes, H.A., Jolliet, O., Finnveden, G., Hauschild, M., Krewitt, W., Muller-Wenk, R. (1999) Best Available Practice Regarding Impact Categories and Category Indicators in Life Cycle Impact Assessment, Background Document for the Second Working Group on Life Cycle Impact Assessment of SETAC Europe (WIA-2), International Journal of LCA, 4 (2) pp 66-74.

Udo de Haes, H.A., Jolliet, O., Finnveden, G., Hauschild, M., Krewitt, W., Muller-Wenk, R. (1999) Best Available Practice Regarding Impact Categories and Category Indicators in Life Cycle Impact Assessment, Background Document for the Second Working Group on Life Cycle Impact Assessment of SETAC Europe (WIA-2), International Journal of LCA, 4 (3) pp 167-174.

[1]*Used Oil Recycling Joint Hearing* Before the Subcommittee on Energy and Power and the Subcommittee on Transport and Commerce of the Committee on Interstate and Foreign Commerce House of Representatives, 96th Congress, 2nd Session, H.R. 7833 and S. 2412, Serial No. 96-199, Government Printing Office, (1980) *pp 64.*

[2]*Used Oil Recycling Joint Hearing* Before the Subcommittee on Energy and Power and the Subcommittee on Transport and Commerce of the Committee on Interstate and Foreign Commerce House of Representatives, 96th Congress, 2nd Session, H.R. 7833 and S. 2412, Serial No. 96-199, Government Printing Office, (1980) *pp 65.*

[3]Used Oil Re-refining, *Used Oil Combustion,* Section 10. pp 392-412- ref. 10.1 pp 392, Used Oil Re-Refining Hearing Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

[4]Used Oil Re-refining, *Used Oil Combustion,* Section 10. pp 392-412- ref. 10.8-10.12, Used Oil Re-Refining Hearing Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

[5]Used Oil Re-refining, *Used Oil Combustion,* Section 10. pp 392-412- ref. 10.13-10.17, Used Oil Re-Refining Hearing Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

[6]Used Oil Re-refining, *Resource Conservation,* Section 12. pp 417-424- ref. 12.1, Used Oil Re-Refining Hearing Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

[7]Used Oil Re-refining, *Executive Summary* pp 452-475, Used Oil Re-Refining Hearing Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

[8]Used Oil Re-refining, *Re-refining Processes,* Section 5. pp 281-330-ref. 5.1-5.22, Used Oil Re-Refining Hearing Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development and Demonstration of the Committee on Science and Technology, US House of Representatives, 95th Congress, First Session, December 12, Issue No. 49, US Government Printing Office.

Used Oil Working Group (1997) Study of used Motor Oil recycling in Eleven Selected Countries, American Petroleum Institute.

Vigon, D.A., Harrison, T.L., U.S.E.P.A. Risk Reduction Engineering Laboratory, Life-Cyde Assessment – Inventory Guidelines and Principles, Lewis Publishers, CRC Press 1994.

Viscolube Marketing Brochure, (1999) Viscolube Revivoil, Viscolube IFP Process for Waste Oil Re-refining.

Vold, M., Moller, H. and Moller, J. (1995) *Burning or Re-refining Used Lube Oil?* Life Cycle Assessment of the Environmental Impacts, Stiftelsen Ostfolforskning, Fredriskstad, Norway.

Walters, R.K. (1975) Waste Oil: Headache or Resource? *Industry Paper, Fiber, Plastics and Chemicals* Sheraton Hotel, Cleveland, Ohio.

Waste Oil, Reclaiming Technology, Utilisation and Disposal, Pollution Technology Review No. 166, Mueller Associates, Inc. (1989)

Weinstein, N.J. (1974) Re-Refining Schemes Compared. *Hydrocarbon Processing* **53**, 74-76.

Wentz, C.A., Chiu, S-Y., Habegger, L.J., Martino, L.E. and Peters, R.W. (1988) Design of a Tracking System for Hazardous Waste Minimization. *Environ. Prog.* **7**.

Wentz, C.A. (1989) Waste Minimization and Resource Recovery. *Hazardous Waste Management*, pp. 117-144. McGraw Hill.

Wentz, C.A. and Basler, F. (1991) The Dechlorination of Used Oil Products. *Hazardous Waste and Hazardous Materials*, **8**, 55-67.

Wenzel, H., Hauschild, M., Alting, L. (1997) Environmental Assessment of Products, Volume 1, Methodology, tools and case studies in product development, Chapman and Hall 1st Ed.

Whisman, M.L., Goetzinger, J.W. and Cotton, F.O. (1974) Waste Lubricating Oil Research.

White, A.L., Shapiro, K., (1993) Life Cycle Assessment: A second Opinion, *Environ. Sci. Technol.*, 27 No. 6, 1016-1017.

Appendix A

Summary of used oil legislation in selected countries

France	*Decree of Nov, 21 1979 (No. 79-981)* –Decree imposed obligations and restrictions on collection and elimination of used oil in France. *(Used Oil Working Group, 1997)* *Law No. 95-101, Feb 2, 1995* –Activities such as the elimination of industrial waste are regulated as outlined by this law by regional or international bodies. (*Used Oil Working Group, 1997; Kachler, 1980*)
Germany	*Used Oil Act, 1968* –Law defined used oil management criteria, however a number of problems stemmed from the act's definition of used oil. *Waste Disposal Act, 1972* –A federal ordinance that worked in conjunction with the Used Oil Act of 1968. It was directed at monitoring and regulating all wastes including used lubricating oils. *Waste Oil Ordinance, 1987* –Replaced the waste oil act of 1968. The act revised the definition of used lube oils, forbade mixing of used oil with foreign substances and changed regulations associated with the collection of waste oils. *Waste Avoidance and Disposal Act, 1996* –The main goal of the act is to integrate direct waste management and regulation to more of a recycling economy, and avoid production of waste as much as is possible in all stages of the production process. (*Used Oil Working Group, 1997*)
Brazil	*Resolution No. 9, 1993* – Consists of 16 articles that control the collection and disposal of used lubricating oils (*Used Oil Working Group, 1997*)
Japan	Waste oil in Japan is subject to the *Waste Disposal and Public Cleaning Act*, which addresses both industrial wastes and other forms of wastes (*Used Oil Working Group, 1997*)
USA	*Resource Conservation and Recovery Act, 1976* –Establishes the framework for the federal government's program of solid and hazardous waste regulation. *Used Oil Recycling Act, 1980* –Designed to establish a discretionary used oil recycling component of state solid waste plans authorised under the act to remove certain impediments to increased recovery and re-use of such oil. (*Biering, 1993*)
European Community	*Used Oil Directive 75/439, 1975* –Its articles promote proper disposal of used oil. The articles deal with issues such as; stating that member states ensure proper collection and disposal and prohibit the discharge of waste oil in drains and waterways. Other articles present on other aspects of used oil management. *Used Oil Directive 87/101* –The main points of this amendment are that it favours used oil regeneration over burning, and strengthened controls on contamination and other pollution problems associated with the re-use of used oils. (*Lohof, 1991*)
South Africa	South Africa has no national legislation directed at waste oil management. (*Used Oil Working Group, 1997*)

Appendix B

Specifications for Effluents as given by Department of Water Affairs, and City Drainage By-Laws, South Africa

DEPARTMENT OF WATER AFFAIRS

SPECIFICATION FOR EFFLUENTS
(Max. permissable concentrations)

[all units in mg/ℓ or ppm except as otherwise stated]

	WATER ACT		CITY DRAINAGE BY-LAWS		
	Special Standards (catchment areas)	General Standards (other than catchment areas)	Johannes-burg	Pretoria	Durban
pH	5.5 - 7.5	5.5 - 9.5	6.5 - 12.0	6-10	> 6.0
Fascal coli	NIL	NIL	-	-	-
Dissolved O_2	> 75%	> 75%	-	-	-
Temperature	> 25°C	< 35°C	< 110°F or < 43°C	-	< 110°F
Chemical oxygen demand	30	75	-	500	-
4 hours OA	5	10			
	Not increasing more than 15% above intake	Not increasing more than 500mg/ℓ above intake	-	200	-
			-	-	-
Suspended solids	Max. 10	Max 25	1000	600	600
Na^+	Not more than 50mg/ℓ above intake	Not more than 50 mg/ℓ above intake	-	75	-
Soap, oil & grease	NIL	Max 2.5	400 ppm	400 ppm	125 ppm
Free Cl	NIL	Max 0.1	-	-	1000
Free & saline NH_3	1.0	10	-	-	-
Nitrates (as N)	1.5	-	-	-	-
Phosphate (as P)	2.0	-	-	-	-
As	0.1	0.5	-	-	-
B	0.5	1.0	-	-	-
Hexavalent Cr	-	0.05	-	-	-
Total Cr.	0.05	0.5	50 ppm	20 ppm	50 ppm
Cu	0.02	1.0	50 ppm	20	50
Pb	0.1	0.1	-	-	-
Cd	-	0.05	50	20	50
Fe	0.3	-	-	-	-
Mn	0.1	-	-	-	-
Ni	-	-	50	20	50
Sulphides	0.05	1.0	50	50	20
F	1.0	1.0	-	-	-
Zn	0.3	5.0	50	20	50
Phenols	0.01	0.1	-	-	-
CN	0.5	0.5	20	10	20
Total sugars and starch	-	-	1000	1000	1500
Tar & tar oils not soluble in water	-	-	60	60	60
Insoluble sulphate	-	-	500	-	-
Calcium carbide	-	-	NIL	NIL	NIL
Total sulphates	-	-	-	300	300

SCHEDULE A

ACCEPTANCE OF TRADE EFFLUENT FOR DISCHARGE INTO THE SEWAGE DISPOSAL SYSTEM

No trade effluent shall be accepted for discharge into the sewage disposal system unless it complies with the following conditions.

The effluent shall not contain concentrations of substances in excess of those stated below:-
Large Works general quality limits are applicable when an industries effluent discharges in a catchment leading to a sewage works of greater than 25 Mℓ/d capacity. Small Works quality limits apply for catchments leading to sewage works with less than 25 Mℓ/d capacity.

	GENERAL QUALITY LIMITS		LARGE WORKS > 25 Mℓ/d	SMALL WORKS < 25 Mℓ/d	UNITS
1.	Temperature (°C)		< 44°C	< 44°C	Degrees Celcius
2.	pH		6 < pH < 10	6,5 < pH < 10	pH units
3.	Oils, greases, waxes of mineral origin		50	50	mg/ℓ
4.	Vegetable Oils, greases, waxes		250	250	mg/ℓ
5.	Total sugar and starch	(as glucose)	1 000	500	mg/ℓ
6.	Sulphates in solution	(as $SO^{=}_{4}$)	250	250	mg/ℓ
7.	Sulphides, hydrosulphides and polysulphides	(as $S^{=}$)	1	1	mg/ℓ
8.	Chlorides	(as $Cℓ^{-}$)	1 000	500	mg/ℓ
9.	Flouride	(as F^{-})	5	5	mg/ℓ
10.	Phenols	(as phenol)	10	5	mg/ℓ
11.	Cyanides	(as CN^{-})	20	10	mg/ℓ
12.	Settleable Solids		Charge	Charge	mℓ/ℓ
13.	Suspended Solids		2 000	1 000	mg/ℓ
14.	Total dissolved solids		1 000	500	mg/ℓ
15.	Electrical Conductivity		-	400	mS/m
16.	Anionic Surfactants		-	500	mg/ℓ
17.	C.O.D.		Charge	Charge	mg/ℓ

GENERAL QUALITY LIMITS		LARGE WORKS > 25 Mℓ/d	SMALL WORKS < 25 Mℓ/d	UNITS
Heavy Metal Limits				
18. Copper	(as Cu)	50	5	mg/ℓ
19. Nickel	(Ni)	50	5	mg/ℓ
20. Zinc	(Zn)	50	5	mg/ℓ
21. Iron	(Fe)	50	5	mg/ℓ
22. Boron	(B)	50	5	mg/ℓ
23. Selenium	(Se)	50	5	mg/ℓ
24. Manganese	(Mn)	50	5	mg/ℓ
25. Lead	(Pb)	20	5	mg/ℓ
26. Cadmium	(Cd)	20	5	mg/ℓ
27. Mercury	(Hg)	1	1	mg/ℓ
28. Total Chrome	(Cr)	20	5	mg/ℓ
29. Arsenic	(As)	20	5	mg/ℓ
30. Titanium	(Ti)	20	5	mg/ℓ
31. Cobalt	(Co)	20	5	mg/ℓ
TOTAL METALS		100	20	mg/ℓ

SPECIAL LIMITATIONS

1 No calcium carbide, radio active waste or isotopes
2 No yeast & yeast wastes, molasses spent or unspent
3 No cyanides or related compounds capable of liberating HCN gas or cyanogen
4 No degreasing solvents, petroleum spirit, volatile flammable solvents or any substance which yields a flammable vapour at 21 °C

Appendix C

Analytical results from selected process streams in the Revivoil re-re-refining processes

Appendix C Analytical results from selected process streams in the Revivoil re-re-refining processes

property	unit	feed	distillate	Vacuum residue	PDA residue	DAO	HF Product
Specific gravity		0.894	0.876	0.936	0.942	0.907	0.8721
Total acidity no.	mgKOH/g	4.8	1.3	8.9	6.4	0.8	0.0
Total basicity no.	mgKOH/g	----	----	----	----	----	0.10
Pour point	°C	----	----	----	----	----	-6
Cloud point	°C	----	----	----	----	----	-4
Viscosity @ 40°C	cSt	66.3	104	127	1237	420	47.66
Viscosity @ 100°C	cSt	9.22	4.18	54.2	67.1	28	7.02
Viscosity Index		116	104	127	113	92	104
Ashes	% wt	0.84	0.02	2.8	3.4	0.02	----
Total nitrogen	ppm	950	235	1600	1760	590	48
Sulphur (FX)	% wt	1.03	0.89	1.10	1.21	1.05	0.1375
Chlorine (FX)	ppm	2650	1850	1600	730	590	<5
Conradson carbon	% wt	1.71	0.01	5.77	5.97	0.85	0.0
Flash point. Open cup	°C	----	----	----	----	----	203
PNA (IP346)	% wt	----	----	----	----	----	0.35
Metals (total)	ppm	6457	136	19159	20267	129	2
Ba	ppm	174	<2	590	80	<2	0
Ca	ppm	1490	<2	3329	4257	<2	0
Mg	ppm	121	<2	469	1615	<2	0
B	ppm	28	<2	60	89	<2	0
Zn	ppm	1083	<2	3680	2844	<2	0
P	ppm	1233	125	3720	2589	<2	0
Fe	ppm	103	<1	395	474	72	0
Cr	ppm	5	<1	15	19	15	0
Al	ppm	13	<1	30	57	<1	0
Cu	ppm	26	<1	84	60	1	0
Sn	ppm	40	8	124	5	8	1
Pb	ppm	2105	3	6490	7310	<1	0
V	ppm	1	<1	1	2	<1	0
Mo	ppm	6	<1	17	8	2	0
Si	ppm	17	<1	69	111	17	0
Na	ppm	22	<1	86	748	<1	1

Source: Billon et al, 1995
Note-compositions not given on mass balance basis, analysis based on samples collected from selected streams

APPENDIX D

Information on Data Modules used in construction of computational model for the comparative environmental analysis of used oil management scenarios in South Africa

APPENDIX D. Information on Data Modules used in construction of computational model for the comparative environmental analysis of used oil management scenarios in South Africa

Module	Data Source	Data information and Comments
Refineries average (South Africa)	Aggregated South African Lubricating Base Oil Refineries production data.	Data collected for Safor and Samco lubricating base oil refineries. Based on operation Jan 1998 – Dec 1999.
111 Oil (Other Sources): Production and Transport to Europe.I	Ecobilan module (cf. software licensing agreement). Eco-profiles of the European plastics industry (PWMI, May 1993). Report 2: Olefin feedstock sources (p.8).	No indication on the geographical source of data, Middle East assumed. Average transportation distance calculated as: - 4,800 nautical miles by 100,000 metric ton tanker, plus - 7,900 nautical miles by 250,000 metric ton tanker
401 Electricity (South Africa, 1996): Production.I	Ecobilan module (cf. software licensing agreement). 1) For production and combustion of coal, lignite, heavy fuel oil, natural gas, process gas: Laboratorium für Energiesysteme ETH, Zurich, 1996 2) for breakdown efficiencies: Energy statistics of OECD countries 1995-1996 International energy agency	Representative of average production in South Africa (1996). Production of Electricity in South Africa: Production of fuels and combustion in power plants Breakdown of energy sources in South Africa: - Coal: 93.25% - Lignite: 0% - Fuel Oil: 0% - Natural Gas: 0% - Nuclear: 5.94% - Hydro: 0.82% (assumption: hydro+wind+waves+tide) - Process Gas: 0% (coke oven gas + blast furnace gas) - Free Electricity: 0% (geothermal, solar, biomass and animal products, industrial waste, municipal waste, non-specified assumed being impact free) Import: 0.01% Distribution losses: NA Efficiencies: - Coal: 39.2975% - Lignite: 32.3% - Oil: 38.5% - Natural Gas: 33% - Nuclear: 33% - Hydro: 90%

APPENDIX D. Information on Data Modules used in construction of computational model for the comparative environmental analysis of used oil management scenarios in South Africa

Module	Data Source	Data information and Comments
402 Liquid Petroleum Gas (LPG): Combustion (2).1	Ecobilan module (cf. software licensing agreement). Primary source: for production of LPG: Frishknecht R (1996).Ökoinventare für Energiesysteme. Zûrich: Bundesamt für Energiewirtschaft for forklift combustion of LPG: the EMEP/CORINAIR Atmospheric Emission Inventory Guidebook (CORINAIR 90). kobenhavn: European Envirronnement Agency.	Combustion of LPG Life Cycle Assessment of Packaging Systems for Beer and Soft Drink Energy and Transport scenarios Danish Environmental Protection Agency, 1998 page: 6-7 annex A
403 Steam: Production in Refineries.1	Ecobilan module (cf. software licensing agreement). Eco-profiles of the European plastics industry (PWMI, May 1993). Report 2: Olefin feedstock sources (p.10).	Steam production. Data represent averages for the refineries examined, weighted by the output of steam. Most oil refineries generate steam on-site. The performance characteristics of these plants is an important contributor to processing parameters. Original energy values in Gross Calorific Value have been translated into Net Calorific Value, resulting in a 5% to 10% reduction.
2321 Naphtha: Refining.1	Ecobilan module (cf. software licensing agreement). Laboratorium fur Energiesysteme ETH, Zurïch, 1996 Teil 1, Erdol Page 171-172 primary source: 1) Concawe (Hrsg.), "quality of aqueous effluents from oil refineries in western europe", Concawe report n°84/53, Brussels 1984 2) Concawe (Hrsg.), "oil refineries waste survey -disposal methods, quantities and costs", Concawe report n° 5/89, Brussels 1989. 3) Concawe (Hrsg), "Performance of Oil Industry Pipeline in Western Europe Statistical Summary of Reported Spillages-1994", Concawe report n° 4/95, Brussels 1995 4) <Raffoil 1991> Vertrauliche Informationen einer modernen, westeuropaischen Raffinerie, 1991.	Data on Naphtha Production using extracted oil. This data sheet is representative of European average in 1994. Use of mass allocation rules, employing similar inventory profiles for heavy fuel oil, light fuel oil and diesel oil Omits petroleum fields exploration (0.08%of the calorific value) and extraction. To use this module, do not forget that you must connect the Electricity inflow to an electricity model of your choice.

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Module	Data Source	Data information and Comments
232I Propane (C3H8): Production.2	Ecobilan module (cf. software licensing agreement). Laboratorium fur Energiesysteme ETH, Zurïch, 1996 Teil 1, Erdol Page 171-172 primary source: 1) Concawe (Hrsg.), "quality of aquous effluents from oil refineries in western europe", Concawe report n°84/53, Brussels 1984 2) Concawe (Hrsg.), "oil refineries waste survey -disposal methods, quantities and costs", Concawe report n° 5/89, Brussels 1989. 3) Concawe (Hrsg), "Performance of Oil Industry Pipeline in Western Europe Statistical Summary of Reported Spillages-1994", Concawe report n° 4/95, Brussels 1995 4) <Raffoil 1991> Vertrauliche Informationen einer modernen, westeuropaischen Raffinerie, 1991.	Production of Propane (C3H8) This data sheet is representative of European average in 1994. Use of mass allocation rules, employing similar inventory profiles for heavy fuel oil, light fuel oil and diesel oil Omits petroleum fields exploration (0.08% of the calorific value) and extraction.
241 Toluene (C6H5CH3): Production.1	Ecobilan module (cf. software licensing agreement). Eco-profiles of the European plastics industry (PWMI, May 1993). Report 4 (Polystyrene), p.10	Production of toluene (C6H5OH) Data derived from the production of benzene, which is considered as a co-product of toluene. Data have been obtained for the production of 1.25 million metric tons from 5 separate plants. Original energy values in Gross Calorific Value have been translated into Net Calorific Value, resulting in a 5% to 10% reduction.
403I Heavy Fuel Oil: Combustion (Refinery).1	Ecobilan module (cf. software licensing agreement). Laboratorium fur Energiesysteme ETH, Zurïch, 1996 Teil 1, Erdol Page 154	Combustion of Heavy Fuel Oil in Refinery Representative of the European process in 1992 and 1993. To use this module, do not forget that you must connect the Electricity inflow to an electricity model of your choice.

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Module	Data Source	Data information and Comments
2321 Heavy Fuel Oil: Production.1	Ecobilan module (cf. software licensing agreement). Buwal 132 (1991) A9 adapted by Ecobilan. Adaptation covers CO2 emissions added for what Buwal calls precombustion for fuels production models; cross loop treatment for fuels production models; recalculation from process data when provided in the Buwal, in order to check, calculation updated using recent European electricity model (UCPTE 1990).	Data on primary mining (excludes water, steam or CO2 injection into the oil reservoir). Average transportation (included): - river barge: 1000 km - pipeline: 125 km - tanker: 4500 km Use of mass allocation rules, implying similar inventory profiles for heavy fuel oil, light fuel oil and diesel oil. Omits petroleum fields exploration (0.08% of the calorific value). To use this module, do not forget that you must connect the Electricity inflow to an electricity model of your choice.
241 High Density Polyethylene (HDPE, Bottle): Production.1	Ecobilan module (cf. software licensing agreement). Eco-profiles of the European plastics industry Report 10: POLYMER CONVERSION I. Boustead Brussels May 1997 page: 20-21	Production of 1 kg of bottle of 1 litre (HDPE) Data have been obtained from 7 bottle blowing installations producing 1 litre HDPE bottles. The bottle masses varied between 32 and 54 grams with an average of 43 grams. Data on the conversion processes relate to practices in 1993-1995 The breakdown of energy between the different parts of the system are: resin production: 71.963% resin delivery: 0.19% processing:19.53% packaging: 8.32% most of the emissions arise from the suppliers of the polymer resin and the producers of the fuel used.

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Module	Data Source	Data information and Comments
241 Low Density Polyethylene (LDPE, Film): Production.1	Ecobilan module (cf. software licensing agreement). Eco-profiles of the European plastics industry Report 10: Polymer Conversion I.Boustead Brussels, May 1997 Page 10.	Production of 1000 kg Polyethylene (LDPE) Film Data have been obtained for the production of some 67 000 tonnes of LDPE film per year. Data on the conversion processes relate to practices in 1993-1995 The relative contributions to total energy of the different groups of operations are: 89.62% resin production 0.21% resin delivery 5.99% processing 4.18% packaging
271S Tinned Plate: Production.1	Ecobilan module (cf. software licensing agreement). BUWAL (Bundesamt für Umwelt, Wald und Landschaft) n°250 Bern, 1996 Page 320-321 Primary source: Stoff und Energiverteilungsanalyse einer Produklinie mit verschiedenen Entsorgung wegen am Beispiel einer Weissblech-Konserven dose-Diplomarbeit TU Berlin, 1990.	Production of 1000 kg Tinned Plate The iron ore comes from Sud America, Australia and Canada. All transport included (iron ore: 1000 km by train, 200 km by truck 40t, 21 000 km by frachter; tin: 500 km by train, 1000 km by truck 40 t, 10000 km by frachter; limestone: 800 km by train, 800 km by truck 40t, iron scrap: 500 km by train, 200 km by truck 40 t)
271S Steel Plate: Production	Ecobilan module (cf. software licensing agreement). BUWAL (Bundesamt für Umwelt, Wald und Landschaft) n°250 Bern, 1996 Page: 330-331 Primary source: Stoff und Energiverteilungsanalyse einer Produklinie mit verschiedenen Entsorgung wegen am Beispiel einer Weissblech-Konserven dose-Diplomarbeit TU Berlin, 1990.	The iron ore comes from Sud America, Australia and Canada. All transport included (iron ore: 1000 km by train, 200 km by truck 40t, 21 000 km by frachter; tin: 500 km by train, 1000 km by truck 40 t, 10000 km by frachter; limestone: 800 km by train, 800 km by truck 40t, iron scrap: 500 km by train, 200 km by truck 40 t) 0.4 g Chrome/kg of Steel co - product: 33 kg
blending average	Aggregated blending data for two Blending plants in South Africa (Shell & BP –Blendcor and Engen's LOBP) Data based on day to day logged operations (Jan 1998- July 1999)	Aggregated data assumed representative of South African Blending plant operations

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Module	Data Source	Data information and Comments
900 Steel: Landfill.1	Ecobilan module (cf. software licensing agreement). Buwal 250 (Bundesamt für Umwelt, Wald und Landschaft) Ökoinventare für Verpackung: Band II Bern, 1996 page 453 primary source: Doka G., Huber F., Labhardt A., Menard M., Zimmermann P., Ökoinventare von Entsorgungprozessen-Grundlagen zur Integration der Entsorgung in Ökobilanzen, ESU-Reihe 1/96; Institut für Energietecknik, Gruppe Energie-Stoffe-Umwelt, ETH Zürich, 1996.	Landfill of Steel Bioactive landfill including landfill gas beneficial use treatment of leachates in purification station and treatment of sludges. net calorific value: 6.1 MJ/kg
900 Tinplate: Landfill.1	Ecobilan module (cf. software licensing agreement). Buwal 250 (Bundesamt für Umwelt, Wald und Landschaft) Ökoinventare für Verpackung: Band II Bern, 1996 page: 454-455 primary source: Doka G., Huber F., Labhardt A., Menard M., Zimmermann P., Ökoinventare von Entsorgungprozessen-Grundlagen zur Integration der Entsorgung in Ökobilanzen, ESU-Reihe 1/96; Institut für Energietecknik, Gruppe Energie-Stoffe-Umwelt, ETH Zürich, 1996.	Landfill of Tinplate Bioactive landfill including landfill gas beneficial use treatment of leachates in purification station and treatment of sludges. net calorific value: 6.1 MJ/kg
900 Polyethylene (PE): Landfill.1	Ecobilan module (cf. software licensing agreement). Buwal 250 (Bundesamt für Umwelt, Wald und Landschaft) Ökoinventare für Verpackung: Band II Bern, 1996 page 433 primary source: Doka G., Huber F., Labhardt A., Menard M., Zimmermann P., Ökoinventare von Entsorgungprozessen-Grundlagen zur Integration der Entsorgung in Ökobilanzen, ESU-Reihe 1/96; Institut für Energietecknik, Gruppe Energie-Stoffe-Umwelt, ETH Zürich, 1996.	Landfill of polyethylene (PE, (C2H4)n) Bioactive landfill including landfill gas beneficial use treatment of leachates in purification station and treatment of sludges. moisture:3.6 kg/t density: 920 kg/m3 net calorific value: 39 MJ/kg composition of PE: C (fossil): 841 kg/t O: 16 kg/t H: 141 kg/t N: 0.7 kg/t Cl: 1.7 kg/t

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Module	Data Source	Data information and Comments
		S: 0.5 kg/t ash: 12 kg/t
602S Road Transport (Truck 28 t, Diesel Oil, kg.km).1	Ecobilan module (cf. software licensing agreement). & Rose Foundation Data, 1999 Laboratorium fur Energiesysteme ETH, Zurïch, 1996 Anhang B: Strassengutertransport Page 22. Primary source: M.Maïbach, D.Peter, B.Seilen "Okoinventar Transport; Grundlagen für den ôjologischen Vergleich von Transportsystem und für den Einbezug von Transportsystem in ökobilanzen", SPP Umwelt, Modul 5, Infras Zurîch, 1995.	This is an Ecobilan module with kg.km data supplied from Rose Foundation audit data of Oilkol used oil collection operations, 1999. Distance travelled known; number, types and masses of vehicles used known Combustion of diesel oil in a truck engine (maximum load: 28 t). Data per kg.km. The km value corresponds to the one way distance Data on combustion derived from diesel truck fuel consumption and emissions (maximum and average load: 28 000 kg). The actual load of the truck is 12 000 kg and the empty return is accounted. The consumption of the truck with the maximum load is 36 litres per 100 km.
Used oil storage	Rose Foundation/University of Cape Town (UCT) Department of Chemical Engineering data, 1999	Data based on effluent analyses carried out by UCT Chemical Engineering and used oil collection volumes for Rose Foundation Brakenfell Depot, Cape Town- Rose Foundation Data 1999
Industrial furnace (South Africa) 232S Oil (used-untreated): Incineration. South Africa	Sacks Circle Industries' Stack Emission analyses data & Ecobilan module (cf. software licensing agreement). Laboratorium fur Energiesysteme ETH, Zurïch, 1996 Teil 3, Anhang F: Entsorgungsprozesse Page 52 Primary source: 1) Suter P., " Energiesysteme und Umwelt ", Vorlesungsskript der Abt.IIIA, Institut für Energietechnik, ETH Zürich, Zürich 1990 2) SUISELECTRA, "ergänzungen zum Umweltverträglichkeitsberich" , im Auftrag der CIBA CEIGY , gemäss Verfügung des Bauinspektorates BS, Basel 1988.	Ecobilan module modified for untreated used oil incineration in Sacks Circle industry operations, Bellville Cape Town. net calorific value: 38 MJ/kg composition of oil (used): Assume average composition South African used oil based on Rose Foundation Data, 1999 (see Appendix 3)

APPENDIX D. Information on Data Modules used in construction of computational model for the comparative environmental analysis of used oil management scenarios in South Africa

Module	Data Source	Data information and Comments
232I Heavy Fuel Oil: Production.4	Ecobilan module (cf. software licensing agreement). Buwal 132 (1991) A9 adapted by Ecobilan. Adaptation covers CO2 emissions added for what Buwal calls precombustion for fuels production models; cross loop treatment for fuels production models; recalculation from process data when provided in the Buwal, in order to check, calculation updated using recent European electricity model (UCPTE 1990).	Data module: Avoided impacts of HFO production through use of used oils as source of fuel Data on primary mining (excludes water, steam or CO2 injection into the oil reservoir). Average transportation (included): - river barge: 1000 km - pipeline: 125 km - tanker: 4500 km Use of mass allocation rules, implying similar inventory profiles for heavy fuel oil, light fuel oil and diesel oil. Omits petroleum fields exploration (0.08% of the calorific value). To use this module, do not forget that you must connect the Electricity inflow to an electricity model of your choice.
Preflash	Revivoil Re-refining Process treatment stage Data Sources: Billon et al, 1995; Viscolube Marketing Brochure, 1999; Giovanna et al, 1999	Streams data sourced from Billon et al 1995, analytical results of streams at Hellas Plant Greece, operational since 1993 Utilities data source: Giovanna et al, 1999; Used oil Marketing Brochure, 1999
Thermal deasphalting	Revivoil Re-refining Process treatment stage Data Sources: Billon et al, 1995; Viscolube Marketing Brochure, 1999; Giovanna et al, 1999	Streams data sourced from Billon et al 1995, analytical results of streams at Hellas Plant Greece, operational since 1993 Utilities data source: Giovanna et al, 1999; Used oil Marketing Brochure, 1999
Hydrofinishing	Revivoil Re-refining Process treatment stage Data Sources: Billon et al, 1995; Viscolube Marketing Brochure, 1999; Giovanna et al, 1999	Streams data sourced from Billon et al 1995, analytical results of streams at Hellas Plant Greece, operational since 1993 Utilities data source: Giovanna et al, 1999; Used oil Marketing Brochure, 1999
Propane deasphalting unit	Revivoil Re-refining Process treatment stage Data Sources: Billon et al, 1995; Viscolube Marketing Brochure, 1999; Giovanna et al, 1999	Streams data sourced from Billon et al 1995, analytical results of streams at Hellas Plant Greece, operational since 1993 Utilities data source: Giovanna et al, 1999; Used oil Marketing Brochure, 1999

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Module	Data Source	Data information and Comments
241 Hydrogen (H2, NaCl Electrolysis): Production.1	Ecobilan module (cf. software licensing agreement). Eco-profiles of the European polymer industry (APME) Report 6: Polyvinyl Chloride (Second Edition) I.Boustead May, 1998 Page: 29 to 32	Produced by the electrolysis of an aqueous solution of sodium chloride: 2 NaCl + H2O = 2 NaOH + Cl2 + H2. Includes three types of cells: mercury, diaphragm and membrane cells. Allocation rules: 1. Sodium chloride partitioned between Cl2 and NaOH on the basis of the relative masses of sodium and chlorine: - NaOH: 39.3% - Cl2: 60.7% - H2: 0% 2. Thermal energy totally attributed to NaOH. 3. Electricity partitioned on a mass basis on all co-products: - NaOH: 52.3% - Cl2: 46.4% - H2: 1.3% 4. All emissions partitioned on a mass basis on all co-products: - NaOH: 52.3% - Cl2: 46.4% - H2: 1.3% Original energy values in Gross Calorific Value have been translated into Net Calorific Value, resulting in a 5% to 10% reduction. Data for hydrogen production have been calculated at the same time as those for chlorine.

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Module	Data Source	Data information and Comments
232S Oil (reprocessed): Incineration.	Revivoil Reprocessing Configuration, Sacks Circle Industries' Stack Emission analyses data & Ecobilan module (cf. software licensing agreement). Laboratorium fur Energiesysteme ETH, Zurich, 1996 Teil 3, Anhang F: Entsorgungsprozesse Page 52 Primary source: 1) Suter P., " Energiesysteme und Umwelt ", Vorlesungsskript der Abt.IIIA, Institut für Energietechnik, ETH Zürich, Zürich 1990 2) SUISELECTRA, "ergänzungen zum Umweltverträglichkeitsberich" , im Auftrag der CIBA CEIGY , gemäss Verfügung des Bauinspektorates BS, Basel 1988.	Module is a combination of Revivoil Reprocessing configuration product with modified Ecobilan used oil incineration module with stack composition based on Sacks Circle Industries' Stack Emission analyses data for reprocessed oil incineration net calorific value: 40 MJ/kg
cement kiln		
232S Oil (used-untreated): Incineration. Cement Kiln (Canada, 1975)	Rose Foundation Data, 1999 for RSA used oil composition, Berry et al, 1975 & Ecobilan module (cf. software licensing agreement). Laboratorium fur Energiesysteme ETH, Zurich, 1996 Teil 3, Anhang F: Entsorgungsprozesse Page 52 Primary source: 1) Suter P., " Energiesysteme und Umwelt ", Vorlesungsskript der Abt.IIIA, Institut für Energietechnik, ETH Zürich, Zürich 1990 2) SUISELECTRA, "ergänzungen zum Umweltverträglichkeitsberich" , im Auftrag der CIBA CEIGY , gemäss Verfügung des Bauinspektorates BS, Basel 1988.	Modified Ecobilan Data module for used oil incineration, modified for stack emission results of experiments of waste oil contaminants based on Cement plant study by Berry et al, 1975 using average South African used oil composition from Rose Foundation data, 1999. net calorific value: 38 MJ/kg Assume average composition South African used oil based on Rose Foundation Data, 1999 (see Appendix 3)

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Module	Data Source	Data information and Comments
Tunnel kiln brick furnace 232S Oil (reprocessed): Incineration. Tunnel kiln Brick Furnace (South Africa)	Revivoil Reprocessing Configuration, De Hoop Bricks' Stack Emission and Product analyses data & Ecobilan module (cf. software licensing agreement). Laboratorium fur Energiesysteme ETH, Zurich, 1996 Teil 3, Anhang F: Entsorgungsprozesse Page 52 Primary source: 1) Suter P., " Energiesysteme und Umwelt ", Vorlesungsskript der Abt.IIIA, Institut für Energietechnik, ETH Zürich, Zürich 1990 2) SUISELECTRA, "ergänzungen zum Umweltverträglichkeitsberich" , im Auftrag der CIBA CEIGY , gemäss Verfügung des Bauinspektorates BS, Basel 1988.	Module is a combination of Revivoil Reprocessing configuration product with modified Ecobilan used oil incineration module with stack composition based on De Hoop Bricks' Stack Emission and Product analyses data. Emission analyses data for reprocessed oil incineration taking into account observed interaction of SOx compounds with kiln product net calorific value: 40 MJ/kg

Appendix E

Inventory results for selected used oil management scenarios

Appendix E

inventory results for selected used oil management scenarios

	Flow	Units	burning untreated oil-furnace	burning untreated oil-cement kiln	burning reprocessed oil-furnace	burning reprocessed oil-brick kiln	re-refining used oil
Inputs:	(r) Barium Sulphate (BaSO4, in ground)	kg	-0.0381043	-0.0381043	-0.0257694	-0.0257694	0.0012576
	(r) Bauxite (Al2O3, ore)	kg	0.996958	0.996958	1.02102	1.02102	0.194722
	(r) Bentonite (Al2O3.4SiO2.H2O, in ground)	kg	-3.60E-03	-3.60E-03	-2.43E-03	-0.0024343	0.000118
	(r) Calcium Sulphate (CaSO4, ore)	kg	-0.00530208	-0.00530208	-0.00355985	-0.0035599	0.0001751
	(r) Chromium (Cr, ore)	kg	-7.33E-06	-7.33E-06	-4.95E-06	-4.95E-06	2.40E-07
	(r) Clay (in ground)	kg	5.99E-02	5.99E-02	8.11E-02	0.0811163	0.0274999
	(r) Coal (in ground)	kg	-47.4756	-47.4756	1.94849	1.94849	39.4324
	(r) Copper (Cu, ore)	kg	-3.73E-05	-3.73E-05	-2.52E-05	-2.52E-05	1.22E-06
	(r) Gravel (unspecified)	kg	-7.25E-01	-7.25E-01	-0.486513	-0.486513	0.0239297
	(r) Iron (Fe, ore)	kg	-7.19E-01	-7.19E-01	-3.28E-01	-0.32788	0.151491
	(r) Iron Sulphate (FeSO4, ore)	kg	-0.00168938	-0.00168938	-9.51E-05	-9.51E-05	0.0012435
	(r) Lead (Pb, ore)	kg	-1.16E-05	-1.16E-05	-7.87E-06	-7.87E-06	3.81E-07
	(r) Lignite (in ground)	kg	4.17E+00	4.17E+00	4.19E+00	4.18699	0.871976
	(r) Limestone (CaCO3, in ground)	kg	-8.45773	-8.45773	-0.196366	-0.196366	6.4625
	(r) Manganese (Mn, ore)	kg	-4.27E-06	-4.27E-06	-2.89E-06	-2.89E-06	1.40E-07
	(r) Natural Gas (in ground)	kg	149.02	149.02	179.5	179.5	56.5327
	(r) Nickel (Ni, ore)	kg	-2.48E-06	-2.48E-06	-1.68E-06	-1.68E-06	8.13E-08
	(r) Oil (in ground)	kg	3048.18	3048.18	3062.35	3062.35	556.97
	(r) Pyrite (FeS2, ore)	kg	-6.11E-02	-6.11E-02	-4.13E-02	-0.0413022	0.0020023
	(r) Sand (in ground)	kg	-0.0329235	-0.0329235	-0.0184806	-0.0184806	0.0046995
	(r) Silver (Ag, ore)	kg	-1.85E-07	-1.85E-07	-1.25E-07	-1.25E-07	6.06E-09
	(r) Sodium Chloride (NaCl, in ground or in sea)	kg	0.333987	0.333987	0.422556	0.422556	0.127233
	(r) Sulphur (S, in ground)	kg	1.96E-09	1.96E-09	1.96E-09	1.96E-09	0.000118
	(r) Uranium (U, ore)	kg	0.00015603	0.00015603	0.00031868	0.0003187	0.00023
	(r) Zinc (Zn, ore)	kg	-2.71E-07	-2.71E-07	-1.83E-07	-1.83E-07	8.88E-09
	E Fuel Energy	MJ	13982	13982	20915	20915	9175
	Explosive (unspecified)	kg	-5.18E-05	-5.18E-05	-5.32E-06	-5.32E-06	3.54E-05
	furfural	kg	0.957255	0.957255	0.957255	0.957255	0.130719
	Hydrogen (H2)	kg	0.640624	0.640624	6.41E-01	0.640624	0.0874812
	Iron Scrap	kg	-0.0639507	-0.0639507	-1.33E-02	-0.0133414	0.0215383
	Land Use (II -> III)	m2a	-1.49E-03	-1.49E-03	-1.00E-03	-0.0010021	4.93E-05
	Land Use (II -> IV)	m2a	-0.00181725	-0.00181725	-0.00122011	-0.0012201	6.00E-05
	Land Use (III -> IV)	m2a	-2.06E-06	-2.06E-06	-1.38E-06	-1.38E-06	6.83E-08
	methyl ethyl ketone	kg	0.88362	0.88362	0.88362	0.88362	0.120664
	Raw Materials (unspecified)	kg	-2.68388	-2.68388	-0.319472	-0.319472	1.78314
	short residue	kg	1295.06	1295.06	1295.06	1295.06	176.848
	Steel	kg	0.0732544	0.0732544	0.0732544	0.0732544	0.0119214
	vacuum residue	kg	3759.07	3759.07	3759.07	3759.07	814.118
	Water Used (total)	litre	-270.174	-270.174	6673.94	6673.94	10570.9
	Water: Public Network	litre	3466.05	3466.05	8773.86	8773.86	10057.9
	Water: Unspecified Origin	litre	-3736.13	-3736.13	-2099.92	-2099.92	513.004
	Wood	kg	-0.275291	-0.275291	-0.0163331	-0.0163331	0.204182
Outputs	(a) Acetaldehyde (CH3CHO)	g	-6.70605	-6.70605	-4.89481	-4.89481	0.0003711

Flow	Units	burning untreated oil-furnace	burning untreated oil-cement kiln	burning reprocessed oil-furnace	burning reprocessed oil-brick kiln	re-refining used oil
(a) Acetic Acid (CH3COOH)	g	-26.9315	-26.9315	-19.651	-19.651	0.0054939
(a) Acetone (CH3COCH3)	g	-6.70543	-6.70543	-4.8944	-4.8944	0.0003473
(a) Acetylene (C2H2)	g	-0.469463	-0.469463	-0.0264391	-0.0264391	0.345552
(a) Aldehyde (unspecified)	g	-0.0174515	-0.0174515	-0.0111738	-0.0111738	0.0013662
(a) Alkane (unspecified)	g	-9.27E+01	-9.27E+01	-6.48E+01	-64.8268	2.08101
(a) Alkene (unspecified)	g	-1.79519	-1.79519	-0.988066	-0.988066	0.355956
(a) Alkyne (unspecified)	g	-6.22E-05	-6.22E-05	-4.20E-05	-4.20E-05	2.04E-06
(a) Aluminium (Al)	g	-9.02E+00	-9.02E+00	0.235587	0.235587	6.68999
(a) Ammonia (NH3)	g	1.05E+00	1.05E+00	1.24E+00	1.24452	0.339331
(a) Antimony (Sb)	g	2.99826	0.0282607	-9.80E-05	-9.80E-05	0.0012802
(a) AOX (Adsorbable Organic Halogens)	g	-7.52E-12	-7.52E-12	-4.23E-13	-4.23E-13	5.53E-12
(a) Aromatic Hydrocarbons (unspecified)	g	15.3852	15.3852	17.1962	17.1962	3.01694
(a) Arsenic (As)	g	-5.44E-01	-5.44E-01	-3.62E-01	-0.362484	0.0263724
(a) Barium (Ba)	g	16.8919	4.99185	-0.00611293	-0.0061129	0.0795766
(a) Benzaldehyde (C6H5CHO)	g	-1.12E-08	-1.12E-08	-7.59E-09	-7.59E-09	3.68E-10
(a) Benzene (C6H6)	g	-2.92E+00	-2.92E+00	0.145516	0.145516	1.53609
(a) Benzo(a)pyrene (C20H12)	g	-0.00284306	-0.00284306	-0.00109853	-0.0010985	0.0010656
(a) Berylium (Be)	g	-0.00177073	-0.00177073	-9.98E-05	-9.98E-05	0.0013033
(a) Boron (B)	g	36.1428	-0.635232	1.44133	1.44133	0.734923
(a) Bromium (Br)	g	-0.171316	29.8287	-0.00972303	-0.009723	0.126014
(a) Butane (n-C4H10)	g	-163.73	-163.73	-112.956	-112.956	3.7949
(a) Butene (1-CH3CH2CHCH2)	g	-1.79927	-1.79927	-1.20932	-1.20932	0.0573832
(a) Cadmium (Cd)	g	-1.34E+00	-1.34E+00	-0.922445	-0.922445	0.0342077
(a) Calcium (Ca)	g	1408.77	1408.77	-0.681777	-0.681777	1.01204
(a) Carbon Dioxide (CO2, fossil)	g	5.74E+05	5.74E+05	9.03E+05	9.03E+05	602058
(a) Carbon Monoxide (CO)	g	7.19E+03	5.75E+03	7.15E+03	7150.36	1240
(a) Carbon Tetrafluoride (CF4)	g	-9.02E-06	-9.02E-06	-6.10E-06	-6.10E-06	2.96E-07
(a) Chlorinated Matter (unspecified, as Cl)	g	2.36E-09	2.36E-09	2.36E-09	2.36E-09	1.13E-09
(a) Chlorine (Cl2)	g	-4.39E-06	-4.39E-06	-2.45E-07	-2.45E-07	3.24E-06
(a) Chromium (Cr III)	g	0.00877225	0.00877225	11.1867	11.1867	0.787639
(a) Chromium (Cr III, Cr VI)	g	3.32564	0.793636	-0.45147	-0.45147	0.031416
(a) Cobalt (Co)	g	-1.3537	-1.3537	-0.933151	-0.933151	0.0337973
(a) Copper (Cu)	g	2.70E+01	-1.99E+00	-1.38E+00	-1.37585	0.0580364
(a) Cyanide (CN-)	g	0.049711	0.049711	0.0519526	0.0519526	0.0099243
(a) Dioxins (unspecified)	g	7.34E-07	7.34E-07	7.56E-07	7.56E-07	1.34E-07
(a) Ethane (C2H6)	g	-1417.39	-1417.39	-989.304	-989.304	28.0716
(a) Ethanol (C2H5OH)	g	-13.4106	-13.4106	-9.78865	-9.78865	0.0006872
(a) Ethylbenzene (C8H10)	g	-1.80E+00	-1.80E+00	-1.21E+00	-1.20508	0.0594112
(a) Ethylene (C2H4)	g	-1.89E+01	-1.89E+01	-1.04E+01	-10.3679	3.33385
(a) Fluorides (F-)	g	1.58E-05	1.58E-05	2.35E-05	2.35E-05	9.47E-06
(a) Fluorine (F2)	g	-2.38E-06	-2.38E-06	-1.34E-07	-1.34E-07	1.75E-06
(a) Formaldehyde (CH2O)	g	-20.258	-20.258	-14.7361	-14.7361	0.0541101
(a) Halogenated Matter (unspecified)	g	-9.88E-14	-9.88E-14	-5.56E-15	-5.56E-15	7.27E-14
(a) Halon 1301 (CF3Br)	g	-0.203681	-0.203681	-0.13674	-0.13674	0.0067406
(a) Heptane (C7H16)	g	-17.9913	-17.9913	-12.0923	-12.0923	0.573787
(a) Hexane (C6H14)	g	-35.9827	-35.9827	-24.1846	-24.1846	1.14757
(a) Hydrocarbons (except methane)	g	3.70E+02	3.62E+02	2585.21	2585.21	1344.86
(a) Hydrocarbons (unspecified)	g	8107.57	8107.57	9383.11	9383.11	2992.99
(a) Hydrogen (H2)	g	-2.03E-06	-2.03E-06	-1.14E-07	-1.14E-07	59.8286
(a) Hydrogen Chloride (HCl)	g	-98.9428	-98.9428	-40.3363	-40.3363	33.4804
(a) Hydrogen Fluoride (HF)	g	-4.65031	-4.65031	-1.37057	-1.37057	1.71903

Flow	Units	burning untreated oil-furnace	burning untreated oil-cement kiln	burning reprocessed oil-furnace	burning reprocessed oil-brick kiln	re-refining used oil
(a) Hydrogen Sulphide (H2S)	g	-1.50048	-1.50048	-0.267677	-0.267677	0.888946
(a) Iodine (I)	g	-0.0428375	-0.0428375	-0.00244909	-0.0024491	0.0314894
(a) Iron (Fe)	g	143.954	143.954	-1.63727	47.2692	3.08015
(a) lanthanum (La)	g	-0.00284212	-0.00284212	-0.00016006	-0.0001601	0.002092
(a) Lead (Pb)	g	1440.63	214.081	22.2674	13.508	1.79051
(a) Magnesium (Mg)	g	1.76E+02	-1.37E+00	1.31E+00	1.31167	2.43048
(a) Manganese (Mn)	g	1.97573	-0.0242503	-0.00461455	-0.0046146	0.0141803
(a) Mercaptans	g	2.36E-09	2.36E-09	2.36E-09	2.36E-09	1.13E-09
(a) Mercury (Hg)	g	-0.0105589	-0.0105589	-0.00524568	-0.0052457	0.0023171
(a) Metals (unspecified)	g	4.36557	4.36557	4.97274	4.97274	1.51658
(a) Methane (CH4)	g	-35424.6	-35424.6	-24252.7	-24252.7	1074.36
(a) Methanol (CH3OH)	g	-22.798	-22.798	-16.6407	-16.6407	0.0011661
(a) Molybdenum (Mo)	g	6.34336	-0.649639	-0.450374	-0.450374	0.0184805
(a) Nickel (Ni)	g	-24.1967	-26.1947	-17.913	-17.913	0.713077
(a) Nitrogen Oxides (NOx as NO2)	g	5660.14	5760.14	8660.24	8660.24	3588.32
(a) Nitrous Oxide (N2O)	g	-52.0382	-52.0382	-31.2492	-31.2492	4.2517
(a) Organic Matter (unspecified)	g	-0.0292963	-0.0292963	-0.0182238	-0.0182238	0.0079419
(a) Particulates (unspecified)	g	-1.45E+03	-1.43E+03	-1.76E+02	-231.788	846.011
(a) Pentane (C5H12)	g	-90.8387	-90.8387	-61.0511	-61.0511	2.90191
(a) Phenol (C6H5OH)	g	-8.61E-08	-8.61E-08	-5.82E-08	-5.82E-08	2.82E-09
(a) Phosphorus (P)	g	622.92	12.3803	1.48588	1.48588	0.163492
(a) Phosphorus Pentoxide (P2O5)	g	-5.41E-05	-5.41E-05	-3.04E-06	-3.04E-06	3.98E-05
(a) Polycyclic Aromatic Hydrocarbons (PAH, u	g	-0.0297402	-0.0297402	-0.0212548	-0.0212548	0.0002772
(a) Potassium (K)	g	-1.10E+00	-1.10E+00	-7.41E-02	-0.0740766	0.79639
(a) Propane (C3H8)	g	-3.49E+02	-3.49E+02	-2.42E+02	-242.455	795.211
(a) Propionaldehyde (CH3CH2CHO)	g	-3.09E-08	-3.09E-08	-2.09E-08	-2.09E-08	1.01E-09
(a) Propionic Acid (CH3CH2COOH)	g	-3.66E-05	-3.66E-05	-2.47E-05	-2.47E-05	1.26E-06
(a) Propylene (CH2CHCH3)	g	-4.11009	-4.11009	-2.44736	-2.44736	0.4914
(a) Scandium (Sc)	g	-0.00096427	-0.00096427	-5.43E-05	-5.43E-05	0.0007098
(a) Selenium (Se)	g	-0.504199	-0.504199	-0.335227	-0.335227	0.0253313
(a) Silicon (Si)	g	26.4834	26.4834	11.9027	11.9027	10.8351
(a) Sodium (Na)	g	31.7888	-30.5812	-20.4504	-20.4504	1.18192
(a) Strontium (Sr)	g	-1.76E-01	-1.76E-01	-9.94E-03	-0.0099445	0.12989
(a) Sulphur Oxides (SOx as SO2)	g	-4.18E+04	-3.13E+04	-29169	-15431.6	5155.4
(a) Tars (unspecified)	g	6.84E-05	6.84E-05	6.84E-05	6.84E-05	9.86E-06
(a) Thallium (Tl)	g	-0.00088233	-0.00088233	-4.97E-05	-4.97E-05	0.0006494
(a) Thorium (Th)	g	-0.00181872	-0.00181872	-0.00010243	-0.0001024	0.0013387
(a) Tin (Sn)	g	4.99943	0.0994316	5.96154	5.96154	0.419758
(a) Titanium (Ti)	g	6.84E-01	-3.13E-01	-0.0178101	-0.0178101	0.232561
(a) Toluene (C6H5CH3)	g	-12.5845	-12.5845	-8.44815	-8.44815	0.462586
(a) Uranium (U)	g	-0.00176466	-0.00176466	-9.94E-05	-9.94E-05	0.0012989
(a) Vanadium (V)	g	-105.326	-106.326	-72.5904	-72.5904	2.62312
(a) Xylene (C6H4(CH3)2)	g	-7.27E+00	-7.27E+00	-4.82517	-4.82517	0.300541
(a) Zinc (Zn)	g	647.31	-1.04073	4.08558	0.435848	0.446111
(a) Zirconium (Zr)	g	-1.35E-03	-1.35E-03	-7.61E-05	-7.61E-05	0.0009948
(ar) Lead (Pb210)	kBq	-4.03E-02	-4.03E-02	-2.27E-03	-0.0022695	0.0296625
(ar) Polonium (Po210)	kBq	-1.42E-05	-1.42E-05	-9.50E-06	-9.50E-06	4.70E-07
(ar) Potassium (K40)	kBq	-2.16E-06	-2.16E-06	-1.45E-06	-1.45E-06	7.18E-08
(ar) Radioactive Substance (unspecified)	kBq	-0.00032816	-0.00032816	-1.85E-05	-1.85E-05	0.0002415
(ar) Radium (Ra220)	kBq	7.97E-08	7.97E-08	7.97E-08	7.97E-08	3.81E-08
(ar) Radium (Ra226)	kBq	-1.32E-02	-1.32E-02	-7.45E-04	-0.0007454	0.0097477

Flow	Units	burning untreated oil-furnace	burning untreated oil-cement kiln	burning reprocessed oil-furnace	burning reprocessed oil-brick kiln	re-refining used oil
(ar) Radium (Ra228)	kBq	-1.08E-06	-1.08E-06	-7.27E-07	-7.27E-07	3.59E-08
(ar) Radon (Rn220)	kBq	-3.34E-05	-3.34E-05	-2.24E-05	-2.24E-05	1.07E-06
(ar) Radon (Rn222)	kBq	-9.40E-01	-9.40E-01	-3.91E-01	-0.391292	0.30545
(ar) Thorium (Th228)	kBq	-9.16E-07	-9.16E-07	-6.15E-07	-6.15E-07	3.04E-08
(ar) Thorium (Th232)	kBq	-5.83E-07	-5.83E-07	-3.91E-07	-3.91E-07	1.93E-08
(ar) Uranium (U238)	kBq	-1.67E-06	-1.67E-06	-1.12E-06	-1.12E-06	5.53E-08
(s) Aluminium (Al)	g	-4.86E-01	-4.86E-01	1.27E+01	12.6542	12.9996
(s) Arsenic (As)	g	-0.00019433	-0.00019433	-0.00013142	-0.0001314	6.37E-06
(s) Cadmium (Cd)	g	-8.79E-08	-8.79E-08	-5.95E-08	-5.95E-08	2.88E-09
(s) Calcium (Ca)	g	-1.94329	-1.94329	1463.18	1463.18	1464.62
(s) Carbon (C)	g	-1.46E+00	-1.46E+00	1.68E+04	16807.9	14541.7
(s) Chromium (Cr III, Cr VI)	g	-0.00243286	-0.00243286	5.19161	5.19161	5.19354
(s) Cobalt (Co)	g	-8.92E-08	-8.92E-08	-6.03E-08	-6.03E-08	2.92E-09
(s) Copper (Cu)	g	-4.46E-07	-4.46E-07	25.9663	25.9663	25.9673
(s) Iron (Fe)	g	-0.971384	-0.971384	100.612	100.612	101.304
(s) Lead (Pb)	g	-2.04E-06	-2.04E-06	2.07E+03	2069.51	2068.73
(s) Manganese (Mn)	g	-1.94E-02	-1.94E-02	-1.31E-02	-0.0131422	0.0006371
(s) Mercury (Hg)	g	-1.62E-08	-1.62E-08	-1.10E-08	-1.10E-08	5.31E-10
(s) Nickel (Ni)	g	-6.70E-07	-6.70E-07	-4.53E-07	-4.53E-07	2.20E-08
(s) Nitrogen (N)	g	-7.61E-06	-7.61E-06	934.787	934.787	519.346
(s) Oils (unspecified)	g	-0.00288562	-0.00288562	104393	104393	16896
(s) Phosphorus (P)	g	-0.0243312	-0.0243312	1211.74	1211.74	1211.81
(s) Sulphur (S)	g	-0.29151	-0.29151	10126.7	10126.7	7270.85
(s) Zinc (Zn)	g	-0.00730327	-0.00730327	1.13E+03	1125.2	1168.53
(w) Acids (H+)	g	79.7877	79.7877	79.8092	79.8092	14.3823
(w) Aldehyde (unspecified)	g	-0.00020802	-0.00020802	-0.00014072	-0.0001407	6.78E-06
(w) Alkane (unspecified)	g	-12.7938	-12.7938	-8.58909	-8.58909	0.423401
(w) Alkene (unspecified)	g	-1.18096	-1.18096	-0.792834	-0.792834	0.0390827
(w) Aluminium (Al3+)	g	-0.615356	-0.615356	-0.30952	-0.30952	0.140031
(w) Ammonia (NH4+, NH3, as N)	g	-35.6197	-35.6197	-1.40256	-1.40256	28.8518
(w) AOX (Adsorbable Organic Halogens)	g	-0.177745	-0.177745	-0.11827	-0.11827	0.0064532
(w) Aromatic Hydrocarbons (unspecified)	g	-51.194	-51.194	-34.368	-34.368	1.6954
(w) Arsenic (As3+, As5+)	g	-0.0196558	-0.0196558	-0.00599823	-0.0059982	0.0048418
(w) Barium (Ba++)	g	-246.377	-246.377	-165.404	-165.404	8.15383
(w) Barytes	g	-6.89314	-6.89314	-4.66174	-4.66174	0.225996
(w) Benzene (C6H6)	g	-12.7975	-12.7975	-8.59157	-8.59157	0.42353
(w) BOD5 (Biochemical Oxygen Demand)	g	-0.277474	-0.277474	3523.97	3523.97	3524.05
(w) Boron (B III)	g	-1.59603	-1.59603	-1.07149	-1.07149	0.0528249
(w) Cadmium (Cd++)	g	-0.0233374	-0.0233374	-0.0121603	-0.0121603	0.0028352
(w) Calcium (Ca++)	g	-3.16E+03	-3.16E+03	-2.12E+03	-2123.25	104.841
(w) Cerium (Ce++)	g	-0.0981933	-0.0981933	-0.0659314	-0.0659314	0.0032367
(w) Cesium (Cs++)	g	1.90E-06	1.90E-06	1.12E-05	1.12E-05	1.28E-05
(w) Chlorides (Cl-)	g	-4.51E+04	-4.51E+04	-2.80E+04	-27984.2	3009.06
(w) Chlorinated Matter (unspecified, as Cl)	g	-1.09601	-1.09601	-0.74122	-0.74122	0.0359333
(w) Chloroform (CHCl3)	g	-1.18E-06	-1.18E-06	-7.95E-07	-7.95E-07	3.85E-08
(w) Chromium (Cr III)	g	1.53E-01	1.53E-01	1.54E-01	0.154183	0.0249219
(w) Chromium (Cr III, Cr VI)	g	4.22302	4.22302	4.30E+00	4.30127	0.810925
(w) Chromium (Cr VI)	g	-9.60E-08	-9.60E-08	-6.49E-08	-6.49E-08	3.15E-09
(w) Cobalt (Co I, Co II, Co III)	g	-0.0003154	-0.0003154	-0.0002133	-0.0002133	1.03E-05
(w) COD (Chemical Oxygen Demand)	g	-26.7083	-26.7083	4168.77	4168.77	4185.28
(w) Copper (Cu+, Cu++)	g	15.0116	11.0116	11.3559	11.0639	2.033

Flow	Units	burning untreated oil-furnace	burning untreated oil-cement kiln	burning reprocessed oil-furnace	burning reprocessed oil-brick kiln	re-refining used oil
(w) Cyanides (CN-)	g	-0.277539	-0.277539	-0.144764	-0.144764	0.0566929
(w) Dissolved Matter (unspecified)	g	186.815	186.815	227.502	227.502	74.4784
(w) Dissolved Organic Carbon (DOC)	g	-0.387857	-0.387857	-0.262303	-0.262303	0.0127163
(w) Ethylbenzene (C6H5C2H5)	g	-2.36E+00	-2.36E+00	-1.59E+00	-1.58568	0.0781636
(w) Fluorides (F-)	g	9.74E+02	9.74E+02	9.75E+02	974.558	133.381
(w) Formaldehyde (CH2O)	g	-1.49E-08	-1.49E-08	-1.01E-08	-1.01E-08	4.88E-10
(w) Hexachloroethane (C2Cl6)	g	-2.07E-12	-2.07E-12	-1.40E-12	-1.40E-12	6.80E-14
(w) Hydrocarbons (unspecified)	g	70.3116	70.3116	9.32E+01	93.2087	36.7704
(w) Hypochlorite (ClO-)	g	-0.00035319	-0.00035319	-0.00023892	-0.0002389	1.15E-05
(w) Hypochlorous Acid (HClO)	g	-0.00035319	-0.00035319	-0.00023892	-0.0002389	1.15E-05
(w) Inorganic Dissolved Matter (unspecified)	g	27.0225	27.0225	27.0285	27.0285	4.84989
(w) Iode (I-)	g	-9.83736	-9.83736	-6.60426	-6.60426	0.325558
(w) Iron (Fe++, Fe3+)	g	-12.2931	-12.2931	-8.17218	-8.17218	0.50028
(w) Lead (Pb++, Pb4+)	g	304.493	4.49263	4.73375	4.51477	0.834976
(w) Magnesium (Mg++)	g	-81.98	-81.98	-5.50E+01	-55.0256	2.72705
(w) Manganese (Mn II, Mn IV, Mn VII)	g	-4.79307	-4.79307	-3.19188	-3.19188	0.188276
(w) Mercury (Hg+, Hg++)	g	-0.00040884	-0.00040884	-0.00027445	-0.0002745	1.36E-05
(w) Metals (unspecified)	g	13.5794	13.5794	13.5855	13.5855	2.4384
(w) Methylene Chloride (CH2Cl2)	g	-0.00336899	-0.00336899	-0.0022784	-0.0022784	0.0001105
(w) Molybdenum (Mo II, Mo III, Mo IV, Mo V	g	-0.0412368	-0.0412368	-0.0274652	-0.0274652	0.0016149
(w) Nickel (Ni++, Ni3+)	g	1.42E+00	-1.77E-01	1.10E+00	-0.0711665	0.104424
(w) Nitrates (NO3-)	g	-7.16583	-7.16583	-4.49398	-4.49398	0.524495
(w) Nitrites (NO2-)	g	-8.76E-05	-8.76E-05	-5.93E-05	-5.93E-05	2.87E-06
(w) Nitrogenous Matter (Kjeldahl, as N)	g	-0.00186448	-0.00186448	-0.00010478	-0.0001048	0.0013726
(w) Nitrogenous Matter (unspecified, as N)	g	-2.75E+01	-2.75E+01	-9.34E+00	-9.3421	6.06129
(w) Oils (unspecified)	g	13284.3	13284.3	13308.8	13308.8	1832.93
(w) Organic Dissolved Matter (chlorinated)	g	2.36E-09	2.36E-09	2.36E-09	2.36E-09	1.13E-09
(w) Organic Dissolved Matter (unspecified)	g	32658.8	32658.8	32658.8	32658.8	4462.07
(w) Organic Matter (unspecified)	g	135.211	135.211	135.211	135.211	21.2329
(w) Phenol (C6H5OH)	g	3421.56	3421.56	3425.5	3425.5	469.366
(w) Phosphates (PO4 3-, HPO4--, H2PO4-, H3	g	76.5777	0.169297	57.1095	1.3354	4.03231
(w) Phosphorous Matter (unspecified, as P)	g	9.66E-04	9.66E-04	0.00096609	0.0009661	0.000462
(w) Phosphorus (P)	g	-0.40991	-0.40991	-0.275508	-0.275508	0.0130732
(w) Phosphorus Pentoxide (P2O5)	g	-0.00161167	-0.00161167	-9.08E-05	-9.08E-05	0.0011863
(w) Polycyclic Aromatic Hydrocarbons (PAH, u	g	-1.27941	-1.27941	-0.85861	-0.85861	0.042697
(w) Potassium (K+)	g	-434.518	-434.518	-291.711	-291.711	15.6598
(w) Rubidium (Rb+)	g	-0.983725	-0.983725	-0.660418	-0.660418	0.0325556
(w) Salts (unspecified)	g	-1.06181	-1.06181	-0.142038	-0.142038	0.688266
(w) Saponifiable Oils and Fats	g	-480.063	-480.063	-3.22E+02	-322.287	15.8873
(w) Selenium (Se II, Se IV, Se VI)	g	-0.041191	-0.041191	-0.0274626	-0.0274626	0.0015812
(w) Silicon Dioxide (SiO2)	g	-0.00120849	-0.00120849	-0.00081729	-0.0008173	3.96E-05
(w) Silver (Ag+)	g	-0.0590238	-0.0590238	-0.0396253	-0.0396253	0.0019533
(w) Sodium (Na+)	g	-30733.8	-30733.8	-20618.9	-20618.9	1059.78
(w) Strontium (Sr II)	g	-592.224	-592.224	-397.486	-397.486	19.7135
(w) Sulphates (SO4--)	g	-4.87E+02	-5.07E+02	-2.21E+02	-235.729	89.4294
(w) Sulphides (S--)	g	5.13E+03	5.13E+03	5.13E+03	5131.51	700.948
(w) Sulphites (SO3--)	g	-1.76E-05	-1.76E-05	-4.59E-06	-4.59E-06	8.89E-06
(w) Sulphurated Matter (unspecified, as S)	g	-2.05E-05	-2.05E-05	-1.26E-05	-1.26E-05	1.99E-06
(w) Suspended Matter (unspecified)	g	6.05E+02	6.05E+02	6.16E+02	615.683	117.472
(w) Tars (unspecified)	g	9.77E-07	9.77E-07	9.78E-07	9.78E-07	1.41E-07
(w) Tetrachloroethylene (C2Cl4)	g	-5.54E-09	-5.54E-09	-3.90E-09	-3.90E-09	1.02E-10

Flow	Units	burning untreated oil-furnace	burning untreated oil-cement kiln	burning reprocessed oil-furnace	burning reprocessed oil-brick kiln	re-refining used oil
(w) Tin (Sn++, Sn4+)	g	-1.09E-06	-1.09E-06	-6.15E-08	-6.15E-08	8.06E-07
(w) Titanium (Ti3+, Ti4+)	g	-0.0128675	-0.0128675	-0.00858382	-0.0085838	0.0005561
(w) TOC (Total Organic Carbon)	g	-6.43E+02	-6.43E+02	-4.29E+02	-429.094	22.7678
(w) Toluene (C6H5CH3)	g	-1.06E+01	-1.06E+01	-7.14E+00	-7.13883	0.351908
(w) Trichlorethane (1,1,1-CH3CCl3)	g	-1.14E-08	-1.14E-08	-7.73E-09	-7.73E-09	3.75E-10
(w) Trichloroethylene (C2HCl3)	g	-3.14E-07	-3.14E-07	-2.12E-07	-2.12E-07	1.04E-08
(w) Triethylene Glycol (C6H14O4)	g	-0.387857	-0.387857	-0.262303	-0.262303	0.0127161
(w) Vanadium (V3+, V5+)	g	-0.0420927	-0.0420927	-0.0275133	-0.0275133	0.002245
(w) VOC (Volatile Organic Compounds)	g	-34.3671	-34.3671	-23.0722	-23.0722	1.13735
(w) Water (unspecified)	litre	-50.8783	-50.8783	-2.93077	-2.93077	37.3724
(w) Water: Chemically Polluted	litre	-3191.53	-3191.53	-1788.63	-1788.63	428.356
(w) Xylene (C6H4(CH3)2)	g	-92.4786	-92.4786	-62.085	-62.085	3.0605
(w) Zinc (Zn++)	g	81.7308	10.7308	63.7803	11.954	5.74543
(wr) Radioactive Substance (unspecified)	kBq	-3.02E-06	-3.02E-06	-1.70E-07	-1.70E-07	2.22E-06
(wr) Radium (Ra224)	kBq	-4.91862	-4.91862	-3.30209	-3.30209	0.162778
(wr) Radium (Ra226)	kBq	-11.3577	-11.3577	-6.68963	-6.68963	1.4449
(wr) Radium (Ra228)	kBq	-9.83725	-9.83725	-6.60418	-6.60418	0.325556
(wr) Thorium (Th228)	kBq	-19.6746	-19.6746	-13.2084	-13.2084	0.651115
asphalt	kg	903.87	903.87	903.87	903.87	123.429
extracts	kg	826.553	826.553	826.553	826.553	112.871
other refinery products	kg	9.51E+03	9.51E+03	9.51E+03	9510.88	9510.88
Recovered Matter (total)	kg	-0.528369	-0.528369	-0.321552	-0.321552	0.0687642
Recovered Matter (unspecified)	kg	-0.528276	-0.528276	-0.321547	-0.321547	0.0686954
Recovered Matter: Iron Scrap	kg	-9.33E-05	-9.33E-05	-5.25E-06	-5.25E-06	6.87E-05
slack wax	kg	327.676	327.676	327.676	327.676	44.7462
slops (off spec)	kg	5.24649	5.24649	5.25E+00	5.24649	0.716441
vacuum residue	kg	1879.53	1879.53	1879.53	1879.53	557.457
Waste (hazardous)	kg	-7.88E-01	-7.88E-01	-4.60E-01	-0.459962	0.0745695
Waste (incineration)	kg	-0.560411	-0.560411	-0.376379	-0.376379	0.0188082
Waste (municipal and industrial)	kg	21.6409	21.6409	164.638	164.638	56.6323
Waste (total)	kg	-4.53423	-4.53423	166.484	166.484	78.8392
Waste (unspecified)	kg	-10.0533	-10.0533	-0.885421	-0.885421	7.04641
Waste: Highly Radioactive (class C)	kg	-2.30E-05	-2.30E-05	-1.29E-06	-1.29E-06	1.69E-05
Waste: Low Radioactive (class A)	kg	-0.600839	-0.600839	-0.402889	-0.402889	0.0204336
Waste: Mineral (inert)	kg	-11.534	-11.534	3.93466	3.93466	13.1821
Waste: Mining	kg	-1.19368	-1.19368	-0.0670824	-0.0670824	0.878784
Waste: Non Mineral (inert)	kg	-0.0722828	-0.0722828	-0.0483214	-0.0483214	0.0025894
Waste: Non Toxic Chemicals (unspecified)	kg	0.00036709	0.00036709	0.00037007	0.0003701	6.24E-05
Waste: Radioactive	kg	-0.095953	-0.095953	-0.0645024	-0.0645024	0.0030458
Waste: Radioactive (unspecified)	kg	5.45E-06	5.45E-06	1.45E-05	1.45E-05	1.42E-05
Waste: Slags and Ash (unspecified)	kg	-2.47191	-2.47191	-0.111256	-0.111256	1.85944

Appendix F

Calculations to determine Sulphur dioxide emissions and carbon dioxide emissions for the heavy fuel oil production and combustion system

In the production and combustion of HFO in South Africa fuel energy is used in the refinery processes. The fuel energy is supplied as approximately 90% fuel oil and 10 % fuel gas.

The fuel oil will be taken to have a composition of:
84.9% carbon (C)
12.1% hydrogen (H)
3 % sulphur (S)
Heat duty = 42.5 kJ/kg
The fuel gas has an average composition given in Table A.7 (Heat duty =49kJ/kg)

molecular mass	species	volume %	mass %
2	H2	39	3.5
28	N2	2.1	2.6
28	CO	0	0.0
34	H2S	0	0.0
16	C1	14.6	10.5
30	C2	12.2	16.4
28	C2=	2	2.5
44	C3	17.8	35.1
42	C3=	4.2	7.9
58	iC4	6	15.6
56	c4=	1.1	2.8
72	c5	1	3.2
		100	**100**

System where used oil is burned without prior treatment in industrial furnace

From inventory results (see Appendix E) in the scenario where 1000kg of used oil is burned without prior treatment in an industrial furnace, the production of an equivalent energy quantity of HFO requires 17 344MJ.

90 % of this energy is from HFO burning and mass of HFO burned over system life cycle =

0.9*17344/42.5 = 366.7

mass of carbon in oil = (84.9/100)*366.7 = 310.7 kg
Assuming all the carbon burns to CO_2: C + O_2 → CO_2, mass of CO_2 formed = 310.7 kg*(Molar mass CO_2/Molar mass C) = 310.7* (44/12) = **1139.4 kg**

Fuel gas supplies 10 % of energy requirements; = 0.1*17344MJ = 1734.4MJ

Mass of fuel gas burned = 1734.4MJ/49MJ.kg^{-1} = 35.4 kg

Mass of CO_2 produced = **99.3 kg**

Assuming used oil heat duty = 38 MJ/kg, mass of HFO that would have been burned in industrial furnace = 38MJ.kg^{-1}/42.5MJ.kg^{-1} * 1000 = 894 kg HFO

Mass of CO_2 from burning quantity of HFO = 0.849 * 849 kg * (44kg.kmol^{-1}/12kg.kmol^{-1}) = **2783 kg CO_2**

Total mass of CO_2 produced = (1139 + 99.3 + 2783) = **4021 kg**

Mass of sulphur in oil burned over HFO production system = (3/100)*366.7 = 11 kg

Mass of SO_2 produced = 11kg * (Mr SO_2/Mr S) = 11kg * (64kg.kmol-1/32kg.kmol-1) = **22 kg**

Mass of Sulphur in equivalent HFO quantity that would have been burned in industrial furnace =

(38MJ.kg^{-1}/42.5 MJ.kg^{-1}) * 1000kg used oil * (3/100) = 26.7 kg S

Mass of SO_2 produced during combustion = 26.7 * (64kg.kmol-1/32kg.kmol-1) = **53.5 kg SO_2**

System where reprocessed oil is burned in an industrial furnace

Avoided impacts of HFO production life cycle energy demands = 12660 MJ

Mass of HFO burned in production = (0.9 * 12660 MJ)/42.5 MJ.kg^{-1} = 268 kg

Mass of S in HFO = (3/100) * 268 = 8.04 kg

Mass of SO_2 produced = 8.04 kg * (64kg.kmol-1/32kg.kmol-1) = 16.1 kg

Mass of oil burned in furnace after reprocessing = 730 kg

Assuming reprocessed oil has same heat duty as used oil, equivalent mass of HFO that would have been burned = (38 MJkg.-1/42.5MJ.kg-1) * 730 kg = 652.6 kg

Mass of S in HFO = 0.03 * 652.6 kg = 19.6 kg

Mass of SO_2 produced = 19.6 kg * (64kg.kmol-1/32kg.kmol-1) = **39.2 kg SO_2**